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Growing winter sprouting broccoli in unheated high tunnels in New Hampshire

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GROWING WINTER SPROUTING BROCCOLI IN UNHEATED HIGH TUNNELS IN NEW HAMPSHIRE

BY

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ABSTRACT

GROWING WINTER SPROUTING BROCCOLI IN UNHEATED HIGH TUNNELS IN NEW HAMPSHIRE

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University of New Hampshire, December, 2010

Winter sprouting broccoli was grown in a two-year study in unheated high tunnels in Durham, NH. Eleven cultivars were grown in a 9.1 m by 18.2 m unheated high tunnel and evaluated for yield, duration of harvest, and number of days from seed to harvest. Secondary rowcover applications were also evaluated for effects on yield, duration of harvest, number of days from seed to harvest, and for their effects on air temperature at plant height. All cultivars were harvested between March and May of 2008 and 2009. Yields ranged from 0.6 to 1.4 kilograms per meter squared. While mortality was observed in uncovered plants, plants under secondary rowcover in unheated high tunnels survived outdoor temperatures as low as -28°C. Preliminary experiments were conducted to evaluate the effect of planting dates and to study low tunnel environments as alternatives to unheated high tunnels over winter.

CHAPTER I

LITERATURE REVIEW

History and Evolution of Broccoli

Brassica oleracea is a widely polymorphic species comprised of 14 botanical varieties (GRIN), including "Broccoli", generally attributed to those cultivated crops of *Brassica oleracea* var. *italica,* and "Cauliflower", attributed to *B. oleracea* var. *botrytis.* Broccolis may be "sprouting" or "heading" and these may be grouped into colors of green, purple, and white (Gray, 1989; Whealy, 2004). In addition, there are annual, biennial, and perennial varieties. Geography has also played a role in creating distinct forms of similar broccoli types in separate regions of the world. Similar diversity is present in the cauliflowers. This review discusses taxonomy, historical origins, and previous research primarily concerned with the biennial purple and white winter sprouting broccolis (WSB) common in Britain.

Common vegetables confused with WSB are "broccolini" and "broccoli raab". Neither of these vegetables are biennial sprouting broccolis, nor are they considered to be *B. oleracea* var. *italica* or var. *botrytis.* Broccoli raab is a member of *B. rapa* and broccolini is a cross between *B. oleracea* var. *italica* and *B. oleracea* var. *alboglabra* (Chinese Kale, Chinese Broccoli) (Livingston, 2010). Both vegetable crops are commonly available in supermarkets and bear some resemblance to the less-familiar biennial WSB. Also deserving mention are perennial white-sprouting cultivars (e.g. "Ninestar" or "White Star") commonly found in seed catalogs alongside WSB. Due to their perennial habit, they are considered distinct from the biennial sprouting broccolis (Gray, 1989).

Taxonomy

Taxonomy and evolution of broccolis and cauliflowers has been presented by Gray (1982; 1989) and, from a molecular perspective, by Song et al. (1988). Gray (1982; 1985) is frequently referenced in the literature in taxonomic and evolutionary discussions including Wien and Wurr (1997), Hodgkin (1995), and Song et al. (1988). There is a limited volume of literature available that specifically addresses WSB, and what is available originates from Horticultural Research International (HRI), Warwick, England (Gray, 1982; Crisp and Gray, 1985; Crisp, Gray et al., 1985; Gray, 1989). By comparison, peer-reviewed literature is widely available specific to Calabrese, or green-sprouting broccoli, which is perhaps most often thought of by the term "broccoli" in the United States.

Gray (1989) proposes a scheme by which broccoli and cauliflower are classified on comparative ontogeny at marketable maturity. By this scheme, purple WSB and white WSB (early) are classified as *B. oleracea* var. *italica* and white WSB (late) is *B. oleracea* var. *botrytis* (Table 1). A definition of the sprouting broccolis is provided by Crisp and Gray (1985):

> The sprouting broccolis consist of several types of *B. oleracea* var. *botrytis* DC and var. *italica* Plenck which produce side shoots bearing small white, yellow or green cauliflower curds, or clusters of young flower buds whose sepals may be green or purple. They have developed into distinct forms in different parts of the world.

Examples of distinct forms include what is known as "Chinese broccoli" from Asia, Calabrese in North America, sprouting broccolis from Italy, and sprouting broccolis in Britain.

The purple and white WSB are relatively unknown in the United States compared to Calabrese that is widely established in commercial production. In the 1980's, Calabrese was the only *B. oleracea* var. *italica* vegetable to be extensively developed by crop breeding and to be represented by numerous cultivars including both open-pollinated and F1 hybrid varieties (Gray, 1989). It is also known as "Italian green-sprouting broccoli" and is thought to have originated in a region in Italy known as Calabria. Italian immigrants introduced the vegetable to the United States in the early part of the 20th century and from the Americas it was introduced to Britain. Calabrese has been selected for rapid maturity, an annual habit, increased head size, and a decrease in lateral shoot development. The crop is now recognized as a heading vegetable rather than a sprouting vegetable (Crisp and Gray, 1985). These characteristics distinguish Calabrese from the purple- and white-sprouting broccolis that are biennial in habit, are cultivated for lateral shoot development, and are popular garden crops in Britain and elsewhere in Northwestern Europe.

Brassica oleracea is a diploid species with $2n = 2x = 18$. There are no major sterility barriers between *Brassica* species and *B. oleracea* is recognized as an outbreeding species (Hodgkin, 1995). The wild species are biennial or perennial but annual summer crops now exist due to extensive selection, with Calabrese and summer cauliflower representing the most extreme examples. According to Hodgkin, it is unresolved how summer cauliflower, Calabrese, and Chinese kale developed the annual character.

Origin and History

References to the *Brassicas* are found in the classical periods including from the Greeks in 600 BC and notable figures such as Theophrastus (372-287 BC), Cato (200 BC), and Pliny (1st Century AD) (Hodgkin, 1995). The sprouting broccolis are recognized in documented writings from the 16th century when, according to Nieuwof (1969), Delachamp described sprouting broccoli under the name *Brassica asparagoides.* Miller's Gardener's Dictionary of 1724 also refers to a "sprout colliflower" and "Italian asparagus" (Gray, 1982). Vilmorin (1885) describes "Purple Sprouting" or "Asparagus Broccoli" of which many different varieties were cultivated. Vilmorin describes the "Purple Sprouting" broccoli as having non-abortive, thick, fleshy, and purplish shoots arising from the axils of leaves gathered before the flowers opened and used like green asparagus. A variety commonly grown in England was also described with green shoots, abortive flowers, and greenish-yellow heads. De Candolle (1908) makes general references to *B. oleracea* as "cabbages" but specific references to sprouting broccolis are absent from his work.

The sprouting broccolis are thought to have originated from the eastern Mediterranean, though it is unclear when they appeared (Gray, 1982). Considerable diversification is thought to have taken place primarily in Italy and the Mediterranean regions, though there is some suggestion of development along the Atlantic coast

(Hodgkin, 1995). Discussions by Gray (1982) and Hodgkin (1995) are in agreement with earlier observations by De Candolle (1908).

Following more recent molecular studies, Song et al. (1990) propose that cultivated forms of *B. oleracea* originated from a single ancient progenitor similar to wild *B. oleracea.* The earliest cultivated *B. oleracea* was likely a leafy kale from which varieties of kale spread along the Mediterranean Coast and North Atlantic coast from Greece to Wales. There seems to be general agreement in the literature that many cultivated *B. oleracea* crops were derived in Italy but it is less clear how the evolutionary pathway arrived there. It was observed by Giles (1941) and discussed by Gray (1982; 1989) that white WSB is absent from Italy and is likely it evolved separately in Northern Europe from the sprouting broccolis that evolved in Italy and the Mediterranean region. In comparison, forms of purple WSB are found in both regions.

Previous Research on Plant Improvement

Brassica oleracea cultivars have been grown as garden crops since classical times and market crop production was driven by the growth of towns (Hodgkin, 1995). During the 19th and 20th centuries, breeding by mass selection achieved longer production, uniformity, and higher productivity. The outbreeding nature makes it difficult to achieve uniformity except by intense selection from a few parental lines. Development of F1 breeding programs was a major step allowing *B. oleracea* crops to meet the needs of large-scale agriculture (Hodgkin, 1995).

By 1982, purple and white WSB were represented by open-pollinated cultivars maintained by mass selection and were thus highly variable and considered unworked crops (Gray, 1982). In a response to these observations, breeding trials were performed to improve British biennial sprouting broccolis (Crisp and Gray, 1985; Crisp, Gray et al., 1985). Crisp and Gray (1985) characterized WSB as widely popular with amateur growers and easy to grow but unpopular with commercial growers due to poor uniformity, inconsistent maturity time, and overall quality of the marketed product thus resulting in high harvest costs. However, WSB received higher market prices compared to other *Brassicas* due to their popularity with consumers. Crisp and Gray (1985) also noted a short harvest season and observed that time to maturity is largely governed by temperature. This caused harvest to be sporadic in March and early April building to a peak in late April to May and then ceasing abruptly. These were considered poor conditions for marketing and also difficult conditions for maintaining consumer interest.

Crisp and Gray (1985) separated WSB British seedstocks into three categories: purple-sprouting, early-maturing white-sprouting, and late-maturing white-sprouting. The purple-sprouting are described as having a continuous range in maturity time, yield and morphological characters. Early-maturing white-sprouting were described as resembling purple-sprouting broccoli in general morphology but have long fleshy side shoots with small loose clusters of pale yellow or pale green flower buds. The late-maturing white-sprouting were morphologically homogenous with short leafy side shoots bearing small compact white curds. Following breeding trials, the purple WSB and early white WSB were found to be broadly similar in characteristics, with late white WSB distinguished by later maturity and greater yield per plot. Two characteristics of the sprouting broccolis that were observed throughout the trials were "tillering" and "lodging". The late white broccolis produced tillers that added to overall yield. Lodging may lead to increased tillering, but is generally understood to be a detrimental condition (Crisp, Gray et al., 1985).

The desired product from the breeding study documented by Crisp et al. (1985) and Crisp and Gray (1985) were uniform cultivars that would produce quality spears that could be sold in a bundle similar in size to bundles of asparagus with the flower buds branching at the top of the bundles. The ideal plant had spears free of leaves, free of stringy tissues, and uniform stem lengths. Crisp and Gray (1985) showed that increases in yield could be achieved by selections and breeding and that further work was needed to develop an adequate range of maturity.

In a personal correspondence, David Pink of Horticultural Research International, Warwick, England, (November 7, 2008; unreferenced) confirmed that seed from the improved genotypes selected by Crisp and Gray in the HRI project were released to Elsoms Seeds (Elsoms Seeds, Ltd., Spalidng, Lincolnshire, UK) and Tozers Seeds (Tozers Seeds, Ltd., Cobham, Surrey, UK), both of which are major commercial seed providers in England. Elsoms currently maintains a breeding program as a joint venture with Bejo Zaden B.V. of Holland (Elsoms, 2008) and seedstocks are developed so that F1 Hybrids are currently available.

Winter Sprouting Broccoli in the United States

The *Garden Seed Inventory* by Kent Whealy (2004), a survey of non-hybrid vegetable seed available in the United States and Canada, lists 32 open-pollinated broccoli varieties available in 2004, down from 50 in 1981. Of the 32 broccoli varieties, seven are in the category of biennial purple or white WSB available from sixteen different seed companies, including companies such as Thompson and Morgan, Territorial Seed Company, Bountiful Gardens and several other companies that advertise rare vegetables and heirloom vegetables (Table 2). The purple WSB cultivars are most common among sprouting broccoli cultivars in the list of North American companies.

In spite of the availability of some cultivars in the United States, no published research is available for this crop. In many regions, season extension techniques might be required to overwinter the crop, but the extent of inputs required for commercial markets is unknown. High tunnels together with rowcover applications are a likely minimum requirement in cooler regions. Other potential cultural modifications are the use of mulch products, drip irrigation and fertigation, and plant spacing.

Temperature Impacts on Growth and Development of Broccoli

Growth and development of Calabrese is well described, but research specific to the development of WSB is lacking. Therefore, this discussion of broccoli growth and development relies on studies of Calabrese. Studies of broccoli growth and development have examined warm and cold temperature effects (Fontes, Ozbun et al., 1967; Wiebe, 1975; Miller, Konsler et al., 1985; Bjorkman and Pearson, 1998; Tan, Wearing et al., 1999), vernalization and photoperiod (Wurr, Fellows et al., 1995), and predictive harvest maturity models (Tan, Birch et al., 2000).

Floral initiation in broccoli appears to be controlled predominantly by temperature (Fontes, Ozbun et al., 1967; Miller, Konsler et al., 1985; Tan, Birch et al., 2000; Dixon, 2007); however, sunlight may play a minor role at best (Miller, Konsler et al., 1985; Tan, Wearing et al., 1999; Dixon, 2007). Optimum growing temperatures for most members of the Brassicaceae family are between 15°C and 20°C, with the best harvest quality occurring in uniformly cool to moderate temperatures (Rubatzky and Yamaguchi, 1997).

Temperatures in excess of 30°C and below 10°C impede growth, and optimal Calabrese head production occurs between 13°C and 20°C. A growing degree day base temperature of 4.4°C (40°F) is reported in Knott's Handbook for Vegetable Growers (1997). Optimal "approximate monthly temperatures for best growth" are reported as 15.5-18.3°C (60-65°F) for Calabrese with a maximum optimal temperature of 23.9°C (75°F), in general agreement with Rubatzky and Yamaguchi.

As many as five stages of reproductive transition and two phases of apex differentiation are described by Bjorkman and Pearson (1998), based on external changes in the shoot tip of the cultivar "Galaxy". The five stages of reproductive transition are vegetative, straightened, bowed, crowned, and headed. Advancement through the growth stages was characterized by increases in apex width prior to differentiation of the meristem. Differentiation of the meristems occurs in two phases: phase one is noted by the development of axillary meristems and phase two occurs as all meristems produce flower buds. Cool temperatures serve as the environmental trigger that initiates the reproductive transition and apex differentiation (Wurr, Fellows et al., 1995). Miller et al. (1985) and Fontes (1967) describe a juvenile phase that calabrese must complete before reproductive transitions can occur. A model proposed by Wurr (1995) omits the existence of a defined juvenile phase, but concurs that a plant must reach a minimum weight, stem diameter, and number of leaves before it can respond to cold temperatures.

In a normally developing inflorescence, flower buds on an individual head increase in size from the bud primordia at the apical meristem outward to the oldest bud (Bjorkman and Pearson, 1998). A vernalization response is required, but low temperature can accelerate the initiation of floral induction, which damages the broccoli inflorescence (Miller, Konsler et al., 1985; Rubatzky and Yamaguchi, 1997). Tan et al (Tan, Wearing et al., 1999) found that temperatures between -7°C to -9°C were lethal to field grown plants while -5°C was sufficient to kill shoot apices. There is likely some thermal protection of the apical meristem by wrapper leaves while the meristem is in its smallest growth stages.

Floral development is also disrupted at temperatures over 30°C. In the cultivar "Galaxy", this heat injury results in an uneven head where exposed buds have more variable sizes than the uninjured (Bjorkman and Pearson, 1998). The uneven appearance occurs because heat prevents initiation of bud elongation. However, all buds still have normal structure and viable pollen at anthesis. Excessive heat may lead to lack of vernalization response, leafy heads and flower death.

Use of High Tunnels in Season Extension

A simple high tunnel is a pipe or other framework covered by a single layer of 102-152 μm plastic, with no electricity, no automated ventilation, and no supplemental heat (Wells and Loy, 1993; Lamont, 1996; Wells, 1996; Lamont, Orzolek et al., 2003). High tunnels are distinguished from "low tunnels" and "greenhouses" (Wells, 1996). In their simplest forms, high tunnels are temporary structures that allow for earlier cropping in spring and extended harvest in the fall with sturdy designs allowing winter production. These temporary structures may be mobile or constructed at a fixed location. Low tunnels are shorter in height, portable, and removed from a field following their use. A typical greenhouse is a heated permanent structure.

Common high tunnel designs are characterized as Quonset or Gothic, which are usually distinguished by roof curvature and peak height (Blomgren and Frisch, 2007).

The Quonset design is characterized by uniform roof curvature with shorter peak height and the Gothic design is a high pointed peak with a steeply pitched roof to shed snow and has vertical sidewalls.

Horticultural crop production in high tunnels is widely practiced across the United States (Carey, Jett et al., 2009) and a review of the literature indicates increased use and development of high tunnel structures in the past 30 years. Tours of diversified farms in New England reveal a high degree of customization of high tunnel sizes, construction, crop use, rotations, and cultural practices to meet demands of individual cropping systems.

Hardy crops can be overwintered in unheated high tunnels with rowcover, automated ventilation, and frost-free irrigation all contributing to moderate the winter climate. Common overwintering crops include leafy greens for salad mixes, carrots, spinach, leeks, radishes, onion and scallions, watercress, beets, potatoes, and turnips (Coleman, 2009). These crops can be grown in USDA Plant Hardiness Zones 3-5 and their potential for overwintering is subject to the severity of the outdoor climate. Benefits of winter growing include high demand for fresh local produce that otherwise is unavailable, bringing in year-round cash flow for the grower.

Limited peer-reviewed literature documenting overwintering high tunnel use is available; however, anecdotal accounts are more common (Coleman, 1998; Byczynski, 2003; Blomgren and Frisch, 2007; Coleman, 2009). Wien (2009) reported a 2-3°C increase in soil temperature in a 38 m by 9 m Gothic design high tunnel structure in Ithaca, New York, in January covered with a single layer of 150 μm clear polyethylene plastic with an infrared blocking additive. Daytime air temperatures inside the high tunnel were documented as high as 9°C greater than outdoor temperatures and nighttime temperatures were found to be equal to ambient outdoor temperatures.

Vegetable production systems in high tunnels are highly variable from farm to farm and growers employ many practices in high tunnels to enhance their season extension effects. Black plastic mulch laid over raised beds directly impacts the root microclimate by increasing soil temperature and controlling weeds. Raised beds allow soil to warm quickly and improve drainage.

Rowcover culture is an established season extension tool in horticulture crop production (Howell, 2010). Rowcovers serve to modify the microclimate around a plant and are polyethylene covers with slits or pores for ventilation and usually supported by wire half-hoops or are porous non-woven polypropylene fabrics supported by wire hoops or floating over a crop. Primarily, rowcovers offer an increase in daytime temperature and provide a buffer to moderate cool nighttime temperatures. In winter, Coleman (1998) reported a 3.8 to 4.3°C difference between outside temperatures and temperatures inside a high tunnel under rowcover when the outside temperature was -3.9°C. When the outside temperature was much colder (-26.1°C), Coleman documents as much as a 24.4 to 27.2°C difference between the outside temperature and indoor temperature under rowcover.

Non-woven rowcovers are marketed at different weights. A lightweight row cover is 17.7 to 21.2 $g{\cdot}m^{-2}$ (0.5 to 0.6 $oz{\cdot}y^{-2}$) and provides growth enhancement, insect control, and light transmission. Typar® (Autoverters, Inc., Roanoke Rapids, NC, supplier, hereafter refered to as Typar; also known as Dupont 5131), a moderately heavyweight rowcover, measures 44.2 $g{\cdot}m^{-2}$ (1.25 $oz{\cdot}yd^{-2}$) and allows greater light transmission than lighter point-bonded rowcovers because it is constructed of thicker fibers with more open space between fibers (Loy, unpublished, October 20, 2010). Issues that need to be considered when using row covers include increased humidity, need for ventilation, and damage to plant tissues from extended contact during extreme weather.

Previous Research at UNH Woodman Farm

Winter sprouting broccoli was first planted in fall 2006 at UNH Woodman Farm for harvest in Spring 2007 (Sideman, personal correspondence). Plants were grown in 4.3 m x 11.0 m (14 ft x 36 ft) unheated high tunnels as a pilot experiment to evaluate feasibility of overwinter survival in New Hampshire. The following winter, 2007-2008, winter sprouting broccoli cultivars were transplanted into a 9.1 m x 18.2 m (30 ft x 60 ft) unheated high tunnel with automatic ventilation fans and roll-up sides for yield evaluation. Six cultivars (Red Head, Bordeaux, Red Arrow, Red Spear, Claret, and Ninestar) were seeded and transplanted. Of the six cultivars, three (Red Head, Bordeaux, Ninestar) were arranged in a completely random design to test for effects of cultivar type, bed mulch application, rowcover use, and planting date. There were two levels of bed mulch treatment (black plastic and bare ground) and two levels of rowcover treatment (single layer of heavy weight Typar® and uncovered plants). Three seeding dates were used in the experiment: 10 Aug. 2008, 26 Aug. 2008, and 12 Sept. 2008. Plants were started from seed in a greenhouse and transplanted to the 9.1 m x 18.2 m high tunnel on 14 Sept., 26 Sept., and 10 Oct., respectively. Broccoli sprouts were harvested from mid-Mar. 2008 to late-Apr. 2008 and yield differences were compared by analysis of variance.

An analysis of variance (ANOVA, JMP 8) showed that the rowcover treatment increased yield of the winter sprouting broccoli cultivars Red Head, Bordeaux, and

Ninestar ($p<0.05$). Plants under rowcover out-yielded uncovered plants (159.7 g to 95.7 g). Seeding date, mulch type, and cultivar type showed no effect on yield.

The duration of harvest was affected by rowcover treatment and planting date treatment ($p<0.05$). Harvest duration of uncovered treatments was 4.0 weeks compared with 5.4 weeks for covered treatments. Of the three planting dates, the first and second planting dates showed similar harvest durations (4.4 weeks) in contrast to the third planting treatment that was harvested for 5.5 weeks.

Seeding date and a possible interaction between cover and cultivar treatments influenced days to maturity. No interaction was detected between seeding date and cultivar. Seeding date 1 and 3 display the greatest difference in days to maturity, with respective harvests beginning at week 4.2 and 3.4. The average first week of harvest of seeding date 2 was also at week 4.2 but was not significantly different from dates 1 and 3 in a Tukey's HSD test ($p<0.05$). The interaction between cultivar and cover treatments was borderline statistically significant ($p= 0.0521$). Application of rowcover had no effect on the cultivar Ninestar, but did have an effect on both Red Head and Bordeaux (Figure 1). Uncovered treatments of Bordeaux and Red Head were harvested earlier than covered treatments.

These results suggest that factors such as rowcover, planting date, and cultivar produce effects on yield, time to maturity, and the length of harvest season. We hypothesized that a more thorough cultivar trial including additional available varieties could identify those that are more or less suitable for New England winter conditions. Four objectives established at the outset of the experiments were: 1) Identify the highest yielding cultivars suitable for tunnel culture, 2) Identify optimum fall planting dates to maximize yield the following spring, 3) Increase farmer and consumer awareness of potential for commercial production, and, 4) Develop recommendations for cultural practices and cultivars for commercial production of winter sprouting broccoli in New England.

Tables

Table 1. Classification and nomenclature of broccolis and cauliflowers based on ontogeny from Gray (1989).

- *Brassica oleracea* L. Italica group
  - Calabrese and other green-sprouting broccolis
  - True heading broccolis
    - Cape broccoli
    - "Purple Cauliflower" (*Cavolfiore Violeto di Sicilia*)
  - Purple-sprouting broccoli
  - White-sprouting broccoli (early)
- *Brassica oleracea* L. Botrytis group
  - Cauliflower
  - "Heading broccolis" (= winter, winter hardy cauliflower)
  - Perennial broccoli
  - Bouquet broccoli
  - White-sprouting broccoli (late)

Table 2. Availability of biennial sprouting broccoli seed in the United States and Canada[1].

Companies listed as offering non-hybrid biennial sprouting broccoli seeds in 2004[2]	Companies continuing to offer non-hybrid biennial sprouting broccoli seeds in 2010[3] (yes/no).
Thompson and Morgan, Lawrenceburg, IN	Yes
Bountiful Gardens, Willits, CA	Yes
The Cooks Garden, Warminster, PA	No
The Garden Path Nursery	Yes
Horus Botanicals, Salem, AR	Information unavailable
P.L. Rohrer and Bros. Inc., Smoketown, PA	No
Territorial Seeds, Cottage Grove, OR	No
Virtual Seeds, Astoria, OR	Yes
West Coast Seeds, Delta, BC, Canada	Yes
Baker Creek Heirloom Seed, Mansfield, MO	Yes
Botanikka Seeds, Iron Ridge, WI	Yes
Heirloom Seeds	Yes
D. Landreth Seed Co., New Freedom, PA	No
Vegetable Seed Warehouse, Carnesville, GA	No
Western Hybrid Seeds, Inc., Hamilton City, CA	Information unavailable
Peters Seed and Research	No

1. In 2010, the winter sprouting broccoli cultivar "Santee", an F1 Hybrid, was carried by High Mowing Seeds (Wolcott, VT) and Johnny's Selected Seeds (Winslow, ME).
2. Whealy 2004.
3. Following a review of electronic and printed material.

Figures

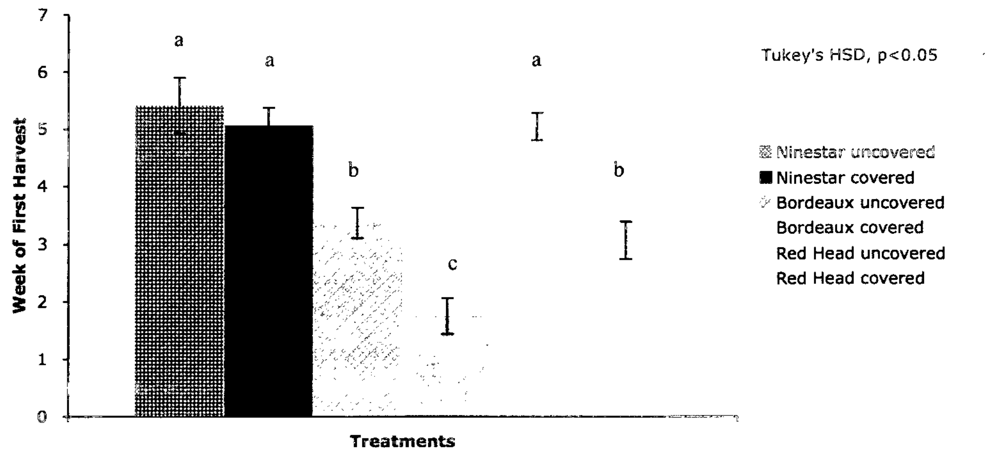

Figure 1. Interaction of cultivar treatment and rowcover treatment on occurrence of first harvest.

CHAPTER II

TEMPERATURE IN A 9.1M BY 18.2M UNHEATED HIGH TUNNEL IN DURHAM, NH, IN JANUARY AND FEBRUARY

Introduction

Winter production in the Northeast is accomplished in high tunnels where it is common for outdoor temperatures to remain below freezing for several days (Coleman, 1998; Byczynski, 2003; Blomgren and Frisch, 2007; Coleman, 2009). Among the advantages of overcoming the harsh environment is the ability to grow local produce when it is otherwise unavailable and in high demand. An additional cultural practice is to add layers of rowcover to enhance growth and mitigate the harsh weather. Traditionally, rowcovers are employed in season extension in spring and fall or during periods of low temperature in the summer (Wells and Loy, 1993; Wells, 1996). The primary function of a rowcover is to enhance growth during periods of low ambient temperature, rather than to provide frost protection.

Rowcovers alone do not provide an effective barrier to heat loss and temperatures under rowcovers at night often equalize or come near to ambient temperatures (Wells and Loy, 1985). However, up to a 3-4°C temperature difference may be achieved under a floating rowcover at night during the summer when soil heat is highest. A significant contributor to heat retention by rowcovers can be condensation that forms on the inside, particularly of polyethylene covers, providing a barrier that is opaque to long wave radiation (Waggoner, 1958, as cited in (Wells and Loy, 1985). In the winter, this moisture barrier may lead to rapid freezing of plant tissues in contact with the floating rowcover at freezing temperatures.

High tunnels function in similar fashion to floating rowcovers: temperatures rise rapidly in the morning after sunrise and after sunset return to near ambient temperatures. Wien (2009) documented this effect in Apr. 2006 and in Jan. 2008 in Ithaca, NY, under clear polyethylene plastic with infrared blocking material. Bonaminio and Bir (1986) also demonstrated this effect under a 102 μm clear plastic high tunnel in North Carolina and observed a 8.1°C (46.5°F) outdoor temperature at 2:00 pm and 29.2°C (84.5°F) in a high tunnel. At 5:00 am the next morning the air temperature was -2.5°C (27.5°F) outside and -3.3°C (26.0°F) in the high tunnel. Soil temperature fluctuations are considerably less than air temperature fluctuations (Wien, 2009).

Akinici et al. (1999) describe low tunnel and high tunnel combinations that provide an average of 5°C higher temperature than outdoors, whereas, low and high tunnels provide average increases of 2°C and 3°C, respectively. A recent non-peer reviewed research document reported approximately 2.8°C difference between high tunnel air and ambient air at night in April, and an approximately 5.5°C difference between outside air and air under a heavy spundbonded low tunnel inside a high tunnel (Wien, Reid et al., 2008).

The objectives of the current study were to: 1) evaluate the effect of one and two layers of 42.2 $g{\cdot}m^{-2}$ (1.25 $oz{\cdot}y^{-2}$) spundbonded rowcover (Typar®, Autoverters, Inc., Roanoke Rapids, NC, supplier; hereafter referred to as "Typar"; also known as Dupont 5131) on air and soil temperature in a high tunnel during winter; and, 2) evaluate the effect of row location on air and soil temperature under uncovered, one or two layers of

Typar rowcover in a high tunnel during winter. This study was conducted at the University of New Hampshire Agricultural Research Station in Durham, NH, from Dec. 2008 to Mar. 2010.

Methods

The temperature experiment was conducted in a 9.1 m by 18.2 m gothic-style unheated high tunnel with 152 μm plastic (four year rating, Klerk's Plastic Products Manufacturing, Richburg, SC), manual roll up sides, and automatic ventilation. Low tunnels were constructed of Typar rowcovers supported by wire hoops or wooden stakes. At the time of the temperature study, there was a winter sprouting broccoli cultivar trial occurring in the high tunnel.

Temperature monitoring was conducted using Hobo U12-008 4-channel outdoor data loggers (Onset Computer Corporation, Bourne, MA). TMC6-HD thermocouple temperature probes connected to the data loggers were arranged to collect air and soil temperature data in three replicates in the high tunnel, and under one layer of rowcover within the high tunnel. Temperatures were logged from Dec. 2008 to Mar. 2009 at 15-minute intervals in the high tunnel environment. Air temperature probes were shielded from sunlight and placed 15 cm high in the plant canopy. Soil temperature was recorded at a depth of 10 cm in the center of raised beds. Temperature probes were arranged to record temperatures in the interior of the high tunnel and along the edge rows of the high tunnel to describe any potential edge effects in the tunnel (Figure 2). The experiment was repeated from Dec. 2009 to Mar. 2010 and conducted in identical fashion to the previous year, but with an additional treatment of two layers of Typar (Figure 3).

The results were summarized for Jan.-Feb. 2009, and Jan.-Feb., 2010 because the most extreme weather occurred in these months and there were no interruptions in data collection. The average temperature of three replications was used to generate monthly average temperatures, standard deviations, minimum temperatures, and maximum temperatures for each treatment. A three-day period surrounding the time when the lowest maximum temperature occurred was selected each year for further analysis and discussion. Cumulative heat units (CHU) were calculated for each year by applying the Baskerville-Emin method (Baskerville and Emin, 1968; Nugent, Undated) to the averaged data for the months of January and February each season.

Results

Seasonal Low Air Temperatures

Temperature regimes with different rowcover treatments on the coldest days in 2009 and 2010 are shown in Figure 4 and Figure 5. Minimum air temperatures occurred just prior to sunrise and increased linearly to a peak at midday and then fell rapidly beginning about two hours before sunset. Similar effects of rowcover treatments are apparent in both years, however the second year (Figure 5) includes data for two layers of Typar. Rowcover effects on temperature compared between sunny and cloudy days are shown in Figure 6 and Figure 7.

The lowest minimum temperature of the entire experiment was -28.1°C and occurred at 7:06 am on 16 Jan. 2009, at UNH Woodman Farm (Figure 4). Concurrently, the average air temperature inside the unheated high tunnel was -16.4°C and the average temperature under the rowcover in middle rows was -10.9°C. A minimum outdoor air temperature in the 2009-2010 growing season of -17.5°C occurred on 30 Jan. 2010, at 6:45 am (Figure 5). The interior high tunnel temperature was -11.0°C, the temperature under a single layer of rowcover was -9.2°C, and under two layers of rowcover was -5.1°C. Average temperatures for the three-day periods in which the lowest minimum temperatures occurred in each season are reported in Table 3. These temperatures are well below the average air temperatures for the month of January and February in both seasons (Table 4). Outdoor air temperatures always remained below indoor high tunnel temperatures and air temperature under rowcover always exceeded the ambient indoor temperature. The average temperature in Jan. 2009 was 2.5°C below normal and the average in February was 0.3°C below normal (Table 4). The average temperature in Jan. 2010 was 1.5°C below normal and in February 2.6°C below normal.

The low temperature events recorded in Figure 4 and Figure 5 represent data collected on clear days. Maximum photosynthetically active radiation (*PAR*) recorded[1] from 15-17 Jan. 2009, was 689.7, 1062.0, and 1058.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ on each of the three days and maximum PAR from 29-31 Jan. 2010, was 1010.0, 1255.0, and 1094.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. On cloudy days, outdoor temperatures equalized and exceeded temperatures inside the unheated high tunnel. Data reported on 25 Jan. 2010 (*PAR* 212.6 $\mu mol \cdot m^{-2} \cdot s^{-1}$; Figure 7) show minimal daily temperature fluctuations and temperatures under a double layer of Typar that are 1-2°C cooler than under single layers of Typar. On 3 Feb. 2009 (PAR 234.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$; Figure 6) a single layer of rowcover exhibited 1-2°C greater temperature than uncovered treatments. Both Figure 6 and Figure 7 illustrate

[1] PAR measurements reported by the "UNH Weather Station", Durham, NH. Data last accessed on October 25, 2010 at www.weather.unh.edu.

large temperature fluctuations on cold sunny days while day and nighttime temperature differentials were minimized on cloudy days.

Although the largest temperatures differential between ambient and high tunnel treatments occurred during the day on clear days, substantive temperature differences also occurred at night. At night, a buffer of 11.7°C was created between outdoor and high tunnel air temperature and a buffer of 17.2°C existed between outdoor air and indoor air under one layer of rowcover when the minimum low temperature event was recorded on 16 Jan. 2009. A less pronounced buffer was recorded in Jan. 2010: 6.5°C between outdoor and high tunnel, 8.3°C between outdoor and indoor under one layer of rowcover, and 12.4°C between outdoor air temperature and indoor air temperature under two layers of rowcover.

Air temperature fluctuation was minimized under two layers of Typar compared to a single layer and uncovered treatments in 2010 (Figure 5). Average air temperatures remained similar, but were slightly higher under two layers of rowcover. However, minimum air temperatures were highest and maximum air temperatures were lowest under two layers of rowcover compared to one. An edge effect is depicted in Figure 5 (29-31 Jan. 2010) where differences in temperature were evident under a double layer of rowcover in the interior of the high tunnel compared with a double layer of rowcover on the edge of the high tunnel. At the minimum low temperature event on 30 Jan. 2010, the temperature under two layers of rowcover in the center of the high tunnel was 4.1°C higher than at the edge row. However, at midday, higher temperatures in the edge row were recorded than in the central locations. The single layer of rowcover and uncovered treatments recorded differences in average temperatures around 1°C between central and edge treatments during the three-day period.

The maximum number of cumulative heat units (CHU) was recorded under a single layer of rowcover during January and February in both seasons (Figure 8, Table 3). The CHUs measured in uncovered treatments also exceeded the results for a double layer of rowcover. The total number of CHUs (base 4.4°C) accumulated in 2010 at the end of February was nearly twice as much under a single layer of rowcover (165.5) than under a double layer (86.9). The total accumulation for an uncovered location within the tunnel was 156.9 CHU compared to 9.3 outdoors.

Soil Temperatures

Soil temperatures under all treatments exhibited minimal differences among treatments and small daily fluctuations. Average soil temperatures of all treatments ranged between 0.5°C and 5.4°C for the months of January and February (Table 6). Average soil temperatures for the reported three day periods in Jan. 2009 and 2010 ranged from 0.6°C to 2.2°C, and were below the monthly averages. The warmest soil temperatures occurred under a single layer of rowcover. Temperature differences between uncovered and single layer treatments were within 0.2°C in 2010 but differed by as much as 1.0°C in 2009. In general, soil temperatures measured in middle rows were higher than edge rows. However, in rows managed similarly with double rowcover, soil temperatures were higher in edge rows than in middle rows (Table 6). Soil temperatures on a cloudy day exhibited approximately 1°C between high and low temperatures (Figure 10). Some variation was present between rowcover treatments on a clear day (30 Jan.

2010), but rowcover treatments on a cloudy day maintained the same relationships throughout. Soil temperatures under a double layer of rowcover were approximately 1°C cooler than soil temperatures under single layered and uncovered treatments.

Discussion

Average and minimum temperatures in both Jan. and Feb. 2009 were cooler than in 2010, indicating 2009 was a cooler winter overall than 2010. During these coldest months, air temperatures inside the unheated high tunnel were consistently higher than outdoor temperatures and rowcovers offered additional temperature gain. These differences in temperature were greatest when outdoor temperatures were lowest. The daily ranges between minimum and maximum air temperatures were greater inside a high tunnel than outdoors particularly on days of direct sunlight and warmer outdoor temperatures. Two layers of rowcover appeared to offer the most protection against fluctuating temperatures as illustrated in Figure 5. Nighttime air temperatures were highest under a double layer and daytime air temperatures were lowest, resulting in the least temperature variation of all rowcover treatments.

While the primary function of rowcovers as described by Wells and Loy (1985) was to enhance growth during periods of low ambient temperatures, this study compared the use of rowcovers as a protective structure to mitigate the effects of freezing temperatures in the winter by providing increased warmth under the cover. In winter conditions (cool temperature and short days), minimal plant growth takes place, as demonstrated by the limited number of recorded CHUs in January and February. In winter 2008-2009, a Typar rowcover application increased average air temperature compared to the high tunnel air temperature. The results for 2009-2010 exhibit fewer differences between Typar and high tunnel temperatures, but this may be due to more complicated arrangements of rowcover blocks and temperature sensors in close spaces. Our results and those of previous investigations (Akinici, Karatas et al., 1999; Wien, Reid et al., 2008) demonstrate that rowcovers can provide a significant temperature buffer, particularly at very low temperatures, that could increase the potential for winter survival of hardy crops.

Possible air temperature influences were present in the soil temperature results for 29-31 Jan. 2010 and are visible as dramatic rises in the temperature chart (Figure 9). These changes were likely due in part to the shallow location (10 cm) of soil temperature probes. Overall, rowcovers had a moderating effect on soil temperature by increasing warming effects during the day and delaying cooling at night.

A slight edge effect was observed for average soil temperatures for all indoor treatments each month and air temperatures under two layers of rowcover in the center of the tunnel were subject to less fluctuation than locations at the edge of the tunnel. This may be explained by two layers of rowcover in the center of the high tunnel having the greatest insulation from outdoor temperatures of all treatments. Soil temperatures show only slight differences between regimes.

Air temperature in the high tunnel rose rapidly in the morning and decreased rapidly at night, but indoor air temperature never appeared to equalize with outdoor air temperature on clear days. However, on a cloudy day in Jan. 2010 the outdoor temperature exceeded indoor temperatures on some occasions. Factors that may have contributed are a lack of solar energy contributing warming effects in soil and insulating qualities of Typar. When temperature differences are minimized on a cloudy day and the outdoor ambient temperature rises at night, the insulating qualities of the high tunnel covering and rowcover applications might delay increases in temperature in the high tunnel. In general, differences between ambient air temperature in the high tunnel and temperature under rowcover within the tunnel were larger at night. This was particularly noticeable in 2009.

Two layers of Typar reduced temperature fluctuations, therefore mitigating extreme events. This may provide less stressful growing conditions for a crop by reducing rapid fluctuations from higher to lower temperatures, especially temperatures below freezing. However, fewer CHUs were recorded under a double layer of rowcover than under a single layer, though the difference was small and not statistically significant. The difference may be of greater importance during growth periods when an additional layer of Typar blocks needed light. Additional research (see Chapter 3) indicates that a single layer of Typar is sufficient for overwintering winter sprouting broccoli and that a double layer of Typar does not increase yields at harvest. Our results in the current study suggest that advantages of using a double layer of Typar occur at night but may not be realized on sunny days and may be blocking desired light. Therefore, it may be possible to employ a system that keeps a second layer of Typar in place at night, but removed on clear sunny days. This would maximize light transmission during the day and maximize heat retention at night.

Tables

Table 3. Air and soil temperatures (°C) on cold sunny days in a 9.1 m x 18.2 m unheated high tunnel with or without rowcover[z] applications on 15-17 Jan. 2009 and 29-31 Jan. 2010 compared to ambient temperatures.

Parameter	Rowcover Application	Average	Min	Max
Air Temperature				
15-17 Jan. 2009				
Outdoor[1]		-15.0	-28.1	-7.6
Middle Row	Uncovered	-5.9	-16.4	14.3
	Single Layer	-2.5	-10.9	15.7
Edge Row	Uncovered	-6.4	-16.9	12.2
	Single Layer	-2.5	-11.5	17.6
29-31 Jan. 2010				
Outdoor		-10.1	-17.5	-0.3
Middle Row	Uncovered	-2.7	-11.0	13.5
	Single Layer	-1.7	-10.0	13.1
	Double Layer	-0.2	-5.2	8.2
Edge Row	Uncovered	-2.4	-10.3	11.4
	Single Layer	-2.5	-10.5	11.9
	Double Layer	-1.7	-9.2	11.5
Soil Temperature				
15-17 Jan. 2009				
Middle Row	Uncovered	0.6	0.1	1.7
	Single Layer	1.2	0.7	2.6
Edge Row	Uncovered	0.3	-0.2	1.4
	Single Layer	0.4	-0.4	1.3
9-31 Jan. 2010				
Outdoor		-3.3	-7.3	0.0
Middle Row	Uncovered	2.2	1.4	3.8
	Single Layer	2.2	1.1	4.3
	Double Layer	1.6	0.7	3.5
Edge Row	Uncovered	1.3	0.5	2.6
	Single Layer	1.3	0.7	2.8
	Double Layer	1.9	0.9	4.3

[z]Typar®, 42.2 $g{\cdot}m^{-2}$ spunbonded polypropylene rowcover.
[y]Outdoor temperature data provided by Cathy Neal at UNH Woodman Farm (HOBO® H21-001 Weather Station, Onset Computer Corp., Bourne, MA).

Table 4. Air temperatures (°C) in a 9.1 m x 18.2 m unheated high tunnel with or without rowcover[z] applications in Jan.-Feb. 2009 and Jan.-Feb. 2010 compared to ambient temperatures.

Parameter	Rowcover Application	Average	Min	Max
Jan. 2009				
Temperature Normals[x]		-4.8	-10.5	0.8
Outdoor Air[y]		-7.3	-28.1	3.5
Middle Rows	Uncovered	-1.8	-16.4	17.3
	Single Layer	0.4	-10.9	19.4
Edge Rows	Uncovered	-2.4	-16.9	14.8
	Single Layer	-0.1	-11.5	17.9
Feb. 2009				
Temperature Normals		-3.1	-8.9	2.7
Outdoor Air		-2.8	-20.0	15.3
Middle Rows	Uncovered	2.9	-12.1	23.7
	Single Layer	5.1	-7.5	25.7
Edge Rows	Uncovered	1.7	-11.9	20.8
	Single Layer	4.0	-7.6	24.8
Jan. 2010				
Temperature Normals		-4.8	-10.5	0.8
Outdoor Air		-3.3	-17.5	11.0
Middle Rows	Uncovered	0.5	-11.0	15.7
	Single Layer	1.2	-10.0	16.3
	Double Layer	1.8	-5.2	11.1
Edge Rows	Uncovered	0.4	-10.3	15.0
	Single Layer	0.5	-10.5	15.7
	Double Layer	0.7	-9.2	15.2
Feb. 2010				
Temperature Normals		-3.1	-8.9	2.7
Outdoor Air		-0.5	-12.6	13.7
Middle Rows	Uncovered	3.0	-8.2	23.2
	Single Layer	3.7	-7.3	22.6
	Double Layer	3.8	-3.9	15.8
Edge Rows	Uncovered	2.8	-7.6	20.7
	Single Layer	3.1	-8.0	22.5
	Double Layer	3.1	-6.9	20.9

[z]Typar®, 42.2 $g \cdot m^{-2}$ spunbonded polypropylene rowcover.
[x]A normal is an average of a climatic element over thirty years (Guttman, 1989). Temperature normals are reported from *Climatography of the United States No. 20 1971-2000* COOP ID 272174.
[y]Outdoor temperature data provided by Cathy Neal at UNH Woodman Farm (HOBO® H21-001 Weather Station, Onset Computer Corp., Bourne, MA).

Table 5. Cumulative Heat Units in a 9.1 m x 18.2 m unheated high tunnel with or without rowcover[z] applications in Jan.-Feb. 2009 and Jan.-Feb. 2010 compared to ambient temperatures.

Parameter	Rowcover Application	Base 4.4	Base 10
Jan. 2009			
Outdoor		0	0
Middle Row	Uncovered	58.6	16.6
	Single Cover	82.6	30.1
Edge Row	Uncovered	38.6	5.5
	Single Cover	68.5	20.1
Feb. 2009			
Outdoor		9.86	1.26
Middle Row	Uncovered	127.8	57.4
	Single Cover	164.6	82.8
Edge Row	Uncovered	85.7	26.8
	Single Cover	135.3	60.4
Jan. 2010			
Outdoor		5.24	0.03
Middle Row	Uncovered	56.3	8.5
	Single Cover	60.9	10.3
	Double Cover	26.1	0.3
Edge Row	Uncovered	42.4	3.9
	Single Cover	47.4	5.3
	Double Cover	39.9	4.0
Feb. 2010			
Outdoor		4.1	0.0
Middle Row	Uncovered	100.6	33.4
	Single Cover	104.7	34.5
	Double Cover	60.8	6.5
Edge Row	Uncovered	80.4	19.8
	Single Cover	93.1	28.3
	Double Cover	86.0	23.2

[z]Typar®, 42.2 g·m^{-2} spunbonded polypropylene rowcover.
[y]Cumulative Heat Units were calculated using the Baskerville-Emin method at base 4.4°C (40°F) and 10°C (50°F).

Table 6. Soil temperatures (°C) in a 9.1 m x 18.2 m unheated high tunnel with or without rowcover[z] applications in Jan.-Feb. 2009 and Jan.-Feb. 2010 compared to ambient temperatures.

Parameter	Rowcover Application	Average	Min	Max
Jan. 2009				
Middle Row	Uncovered	1.3	0.1	5.0
	Single Layer	2.3	0.7	6.0
Edge Row	Uncovered	0.5	-1.1	3.8
	Single Layer	1.6	0.4	5.6
Feb. 2009				
Middle Row	Uncovered	5.0	-2.7	12.1
	Single Layer	5.4	-2.4	11.1
Edge Row	Uncovered	4.0	-10.8	17.3
	Single Layer	4.4	-10.5	11.1
Jan. 2010[y]				
Outdoor		-2.3	-7.3	0.0
Middle Row	Uncovered	3.0	1.4	6.1
	Single Layer	3.0	1.1	6.8
	Double Layer	2.2	0.7	6.1
Edge Row	Uncovered	2.0	0.5	6.0
	Single Layer	2.1	0.7	5.7
	Double Layer	2.5	-2.4	9.4
Feb. 2010				
Outdoor		-0.7	-5.0	2.9
Middle Row	Uncovered	4.3	1.4	7.4
	Single Layer	4.5	1.3	8.1
	Double Layer	3.6	0.8	7.3
Edge Row	Uncovered	3.4	0.6	7.1
	Single Layer	3.5	0.7	6.9
	Double Layer	4.3	-1.3	12.4

[z]Typar®, 42.2 $g \cdot m^{-2}$ spunbonded polypropylene rowcover.
[y]Outdoor soil temperatures reported for 27-31 Jan. 2010.

Figures

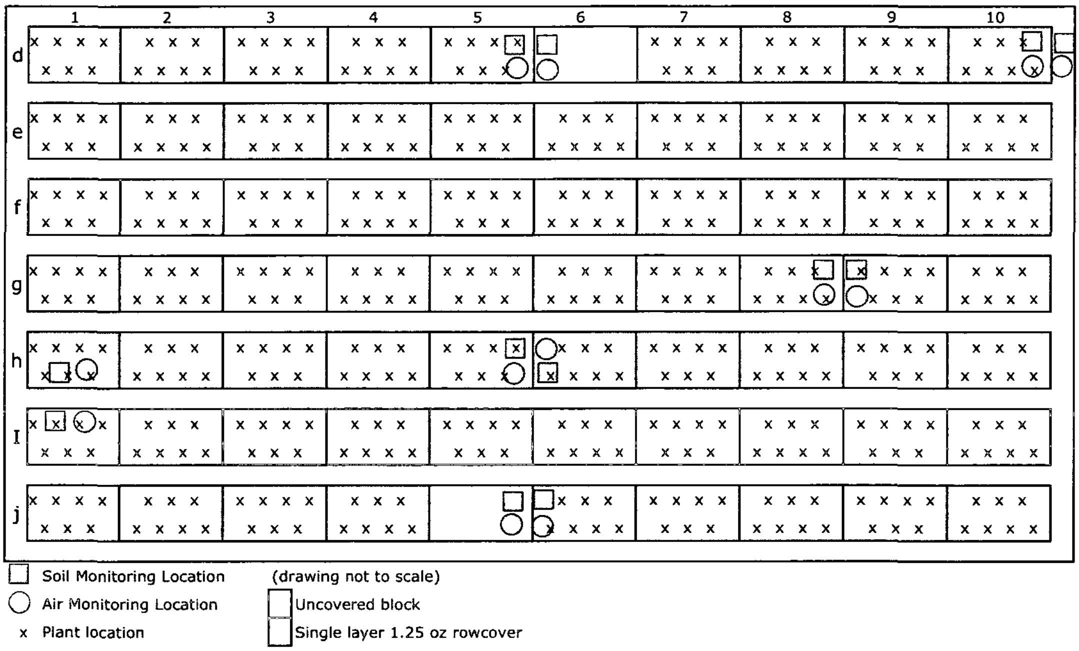

Figure 2. Approximate locations of Hobo® U12-008 data loggers with TMC6-HD thermocouples (Onset Computer Corporation, Bourne, MA) in a 9.1 m x 18.2 m unheated high tunnel with and without rowcover applications from Dec. 2008 to Mar. 2009.

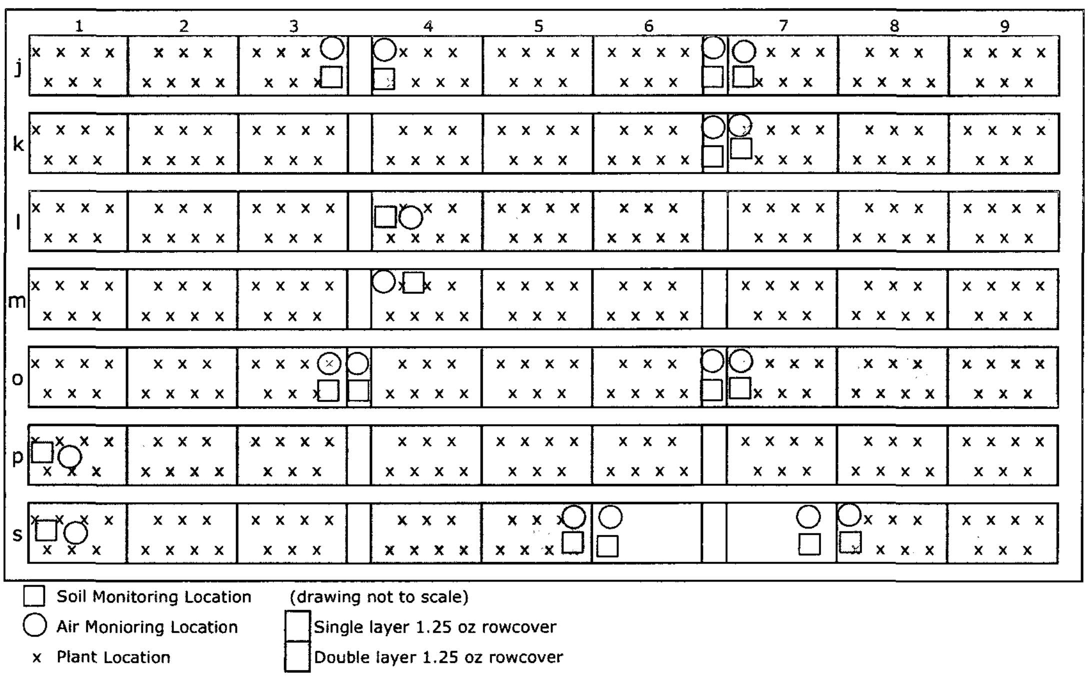

Figure 3. Approximate locations of Hobo® U12-008 data loggers with TMC6-HD thermocouples (Onset Computer Corporation, Bourne, MA) in a 9.1 m x 18.2 m unheated high tunnel with and without rowcover applications from Dec. 2009 to Mar. 2010.

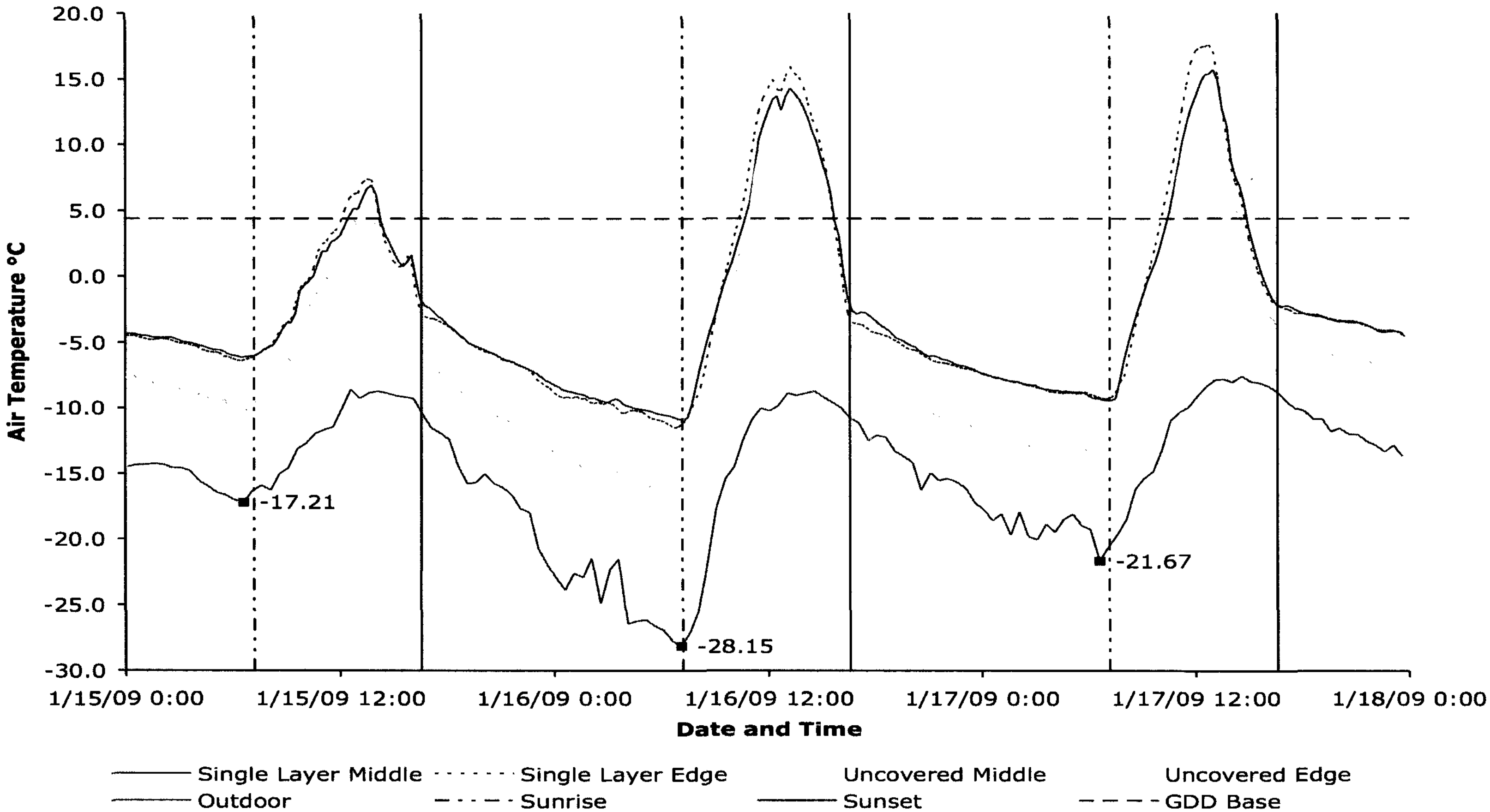

Figure 4. Air temperatures (°C) on cold sunny days in a 9.1 m x 18.2 m unheated high tunnel with or without 42.2 g·m^{-2} spunbonded polypropylene rowcover applications on 15-17 Jan. 2009 compared to ambient temperatures.

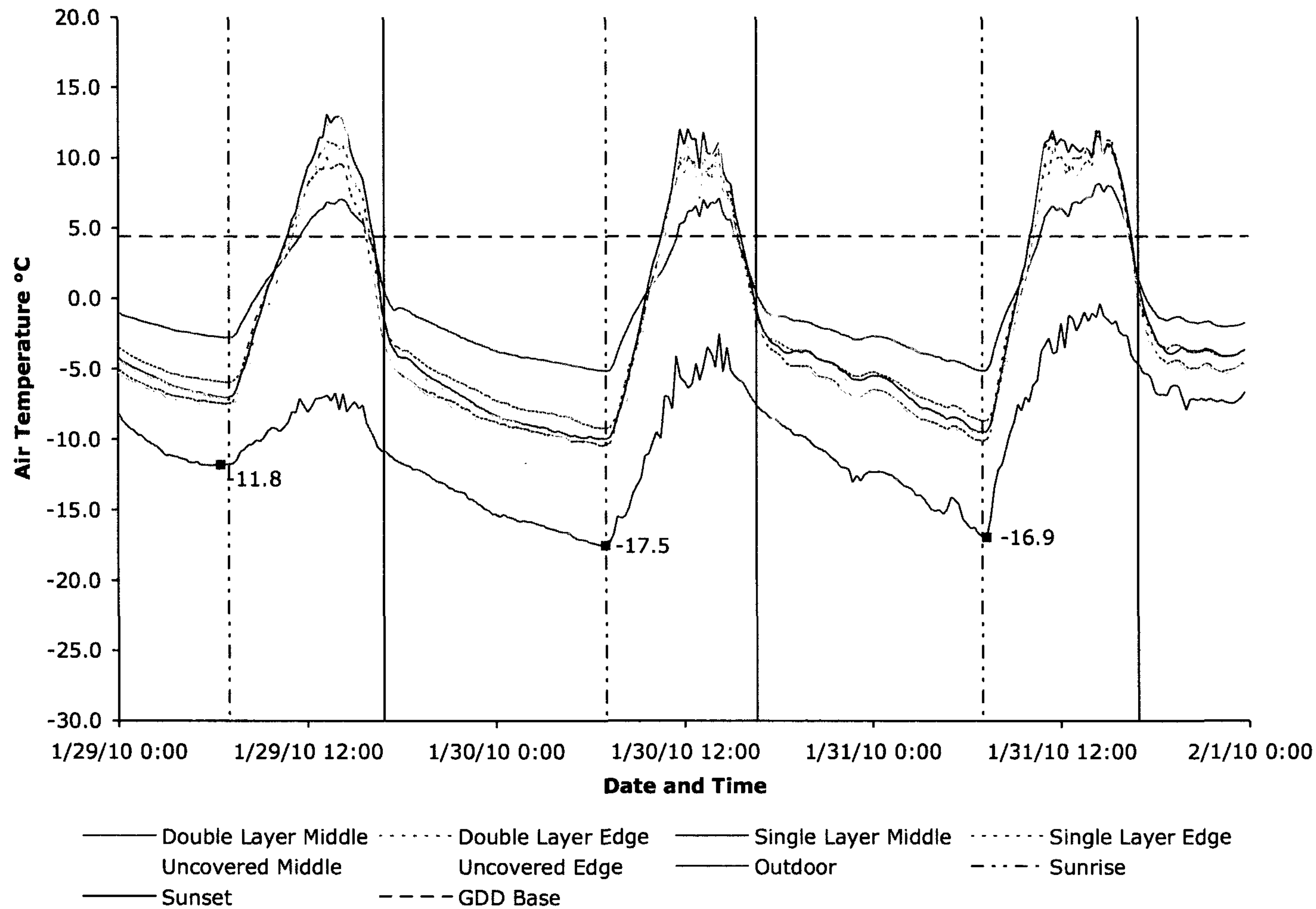

Figure 5. Air temperatures (°C) on cold sunny days in a 9.1 m by 18.2 m unheated high tunnel with or without 42.2 $g \cdot m^{-2}$ spundbonded polypropylene rowcover applications on 29-31 Jan. 2010 compared to ambient temperatures.

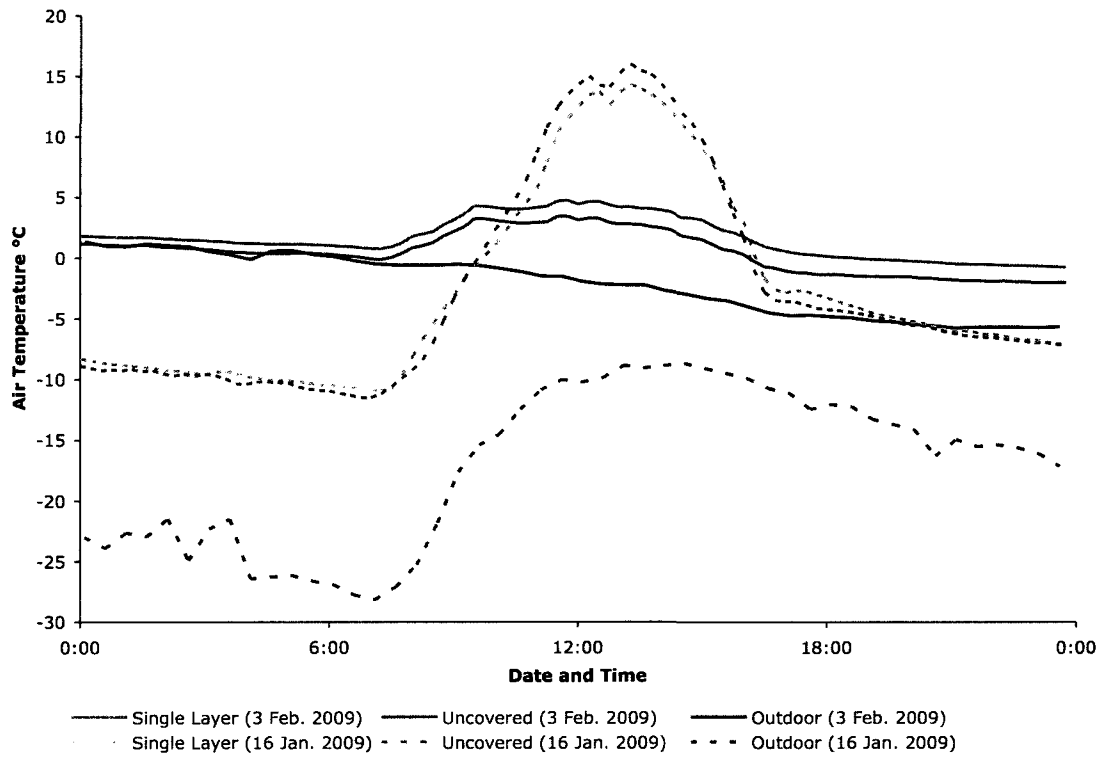

Figure 6. Air temperatures on a cloudy day (3 Feb. 2009) in a 9.1 m by 18.2 m unheated high tunnel with and without 42.2 g·m^{-2} spunbonded polypropylene rowcover applications compared to air temperatures on a sunny day (16 Jan. 2009) with or without rowcover applications.

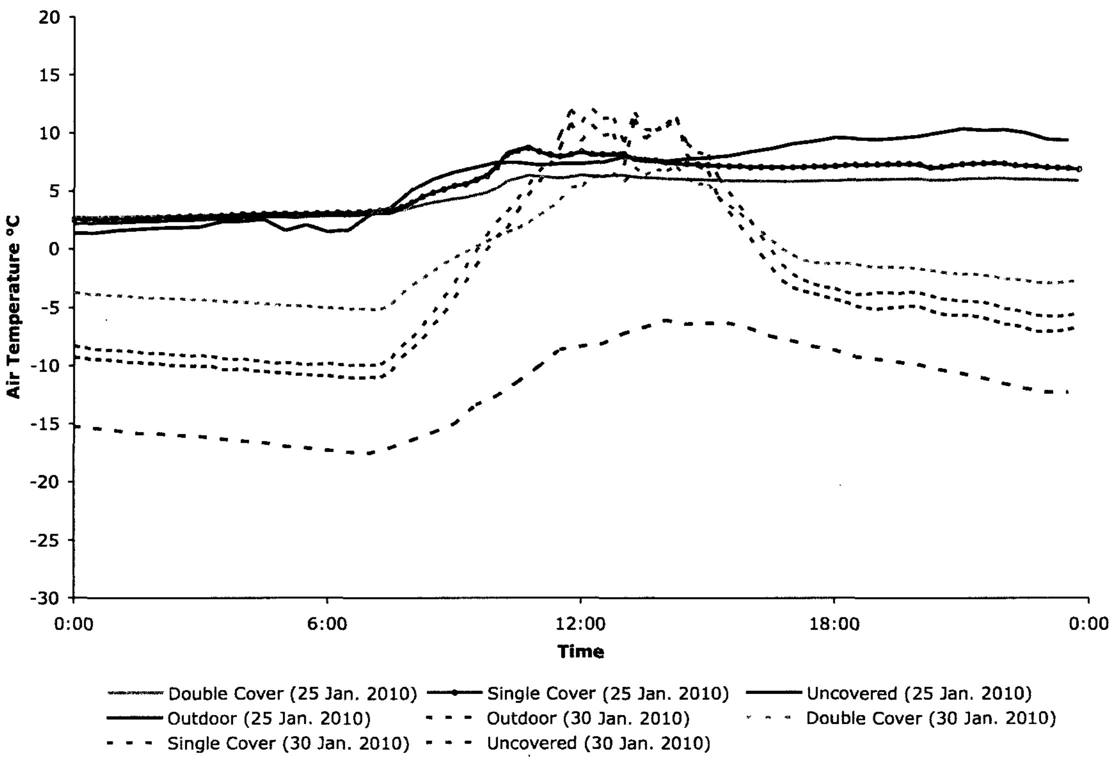

Figure 7. Air temperatures on a cloudy day (25 Jan. 2010) in a 9.1 m by 18.2 m unheated high tunnel with and without 42.2 g·m^{-2} spunbonded polypropylene rowcover applications compared to air temperatures on a sunny day (30 Jan. 2010) with or without rowcover applications.

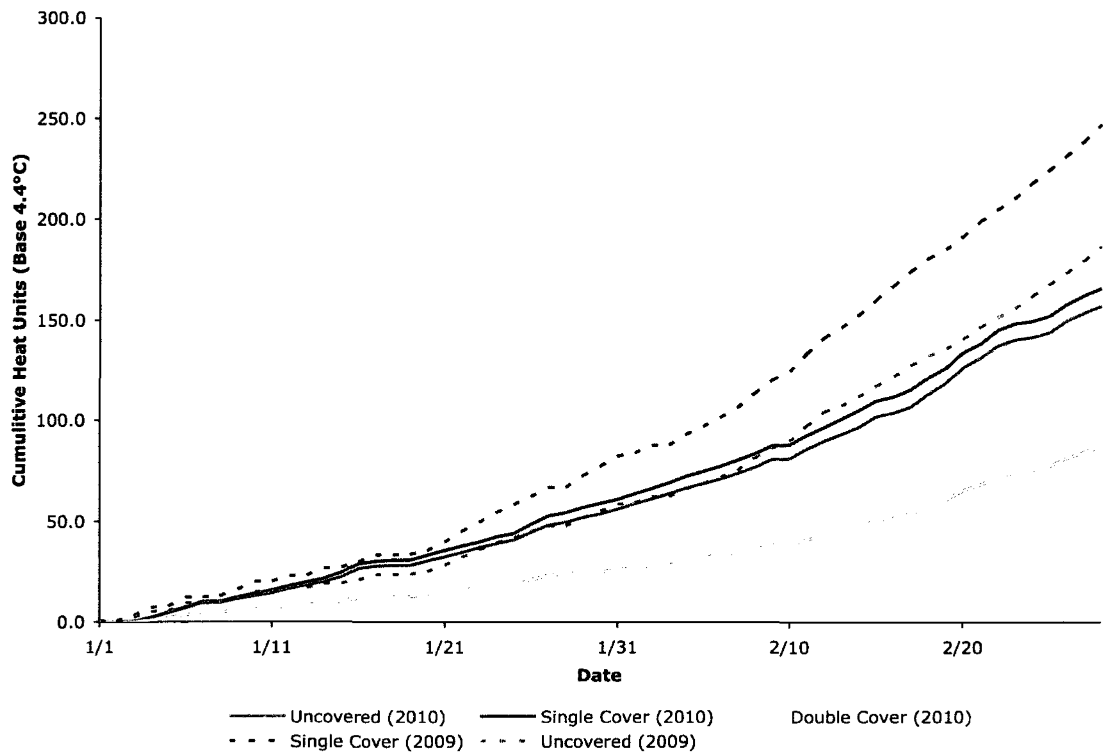

Figure 8. Cumulative Heat Units in a 9.1 m x 18.2 m unheated high tunnel with or without 42.2 $g{\cdot}m^{-2}$ spunbonded polypropylene rowcover applications in Jan.-Feb. 2009 and Jan.-Feb. 2010.

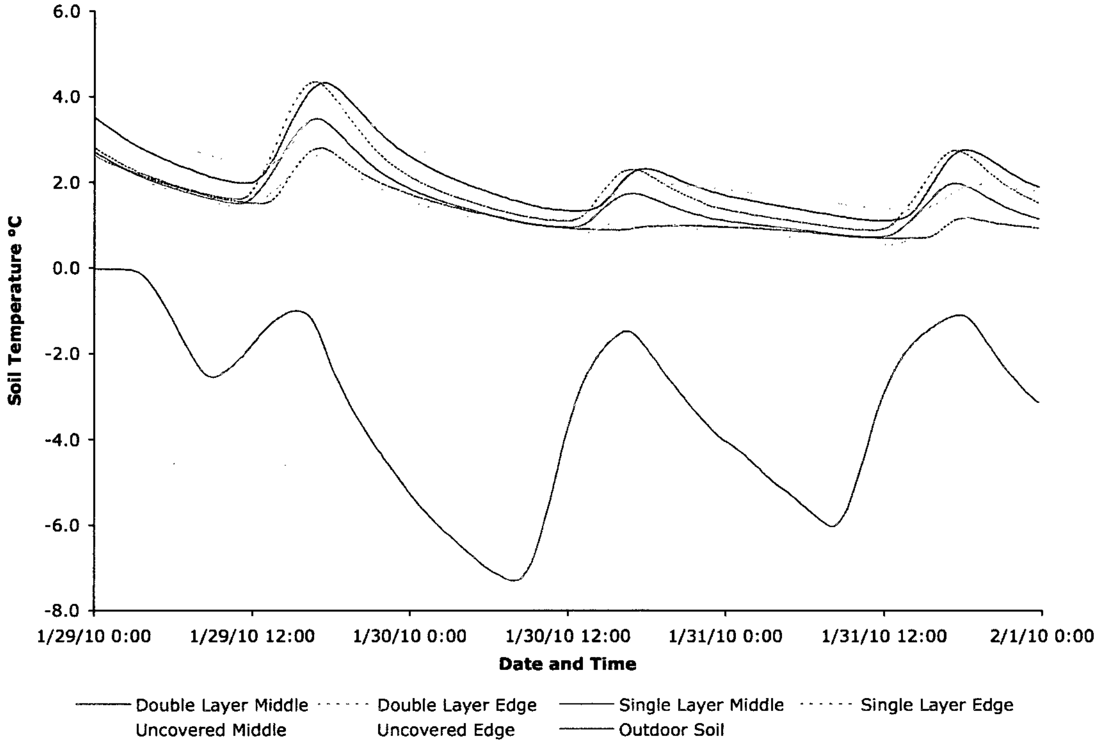

Figure 9. Soil temperatures (°C) on cold sunny days in a 9.1 m x 18.2 m unheated high tunnel with or without 42.2 g·m^{-2} spunbonded polypropylene rowcover applications on 29-31 Jan. 2010 compared to ambient temperatures.

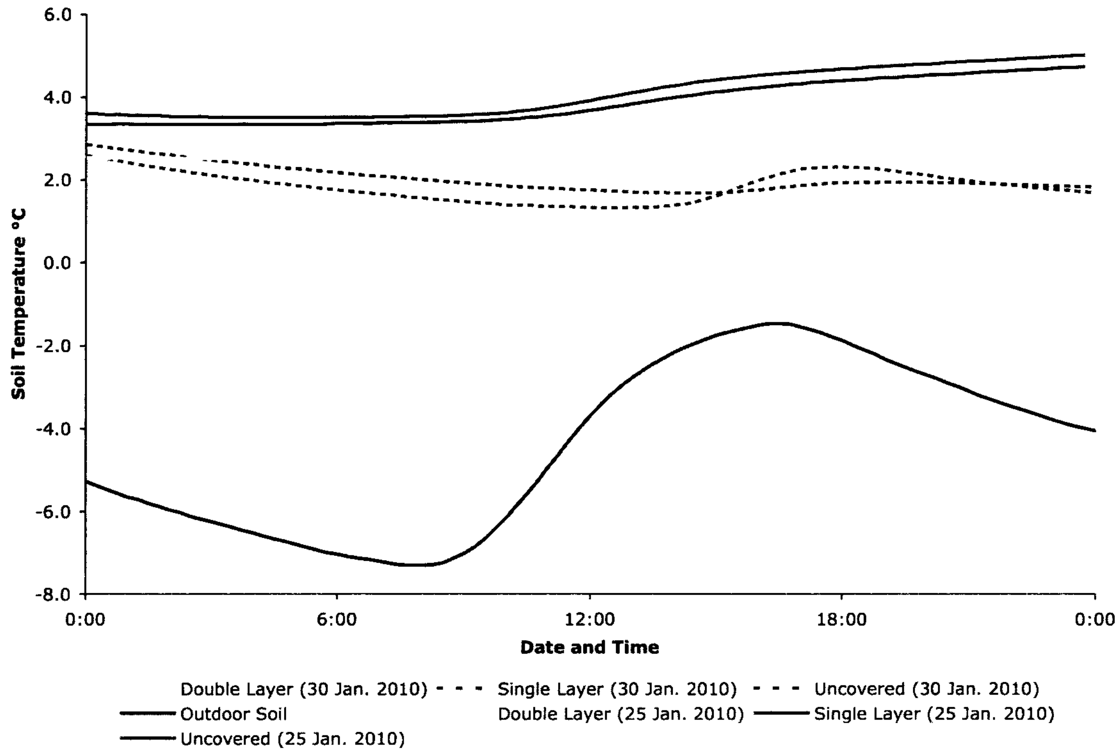

Figure 10. Soil temperatures on a cloudy day (25 Jan. 2010) in a 9.1 m by 18.2 m unheated high tunnel with and without 42.2 g·m^{-2} spunbonded polypropylene rowcover applications compared to soil temperatures on a sunny day (30 Jan. 2010) with or without rowcover applications.

CHAPTER III

THE EFFECT OF CULTIVAR, ROWCOVER, AND ROW LOCATION ON YIELD, DURATION OF HARVEST, AND NUMBER OF DAYS FROM SEED TO HARVEST

Introduction

Winter sprouting broccoli (WSB) is a biennial vegetable that is planted in the fall and harvested in the spring. As an overwintering vegetable, it offers diversified growers an additional source of income in the spring when demand for fresh local produce is high. Previous work at University of New Hampshire (UNH) Woodman Farm, Durham, NH, indicates WSB has potential to be adapted into the New England fresh produce market. Additional studies in cultivation practices were necessary to establish recommended practices for the crop.

Previous breeding research in Britain (Crisp and Gray, 1985; Crisp, Gray et al., 1985) focused on establishing greater uniformity in what was then considered an underutilized crop. This remains the only published research dedicated to crop improvement in WSB, but other sources describe taxonomy, history, and evolution (Giles, 1941; Gray, 1982; Gray, 1989). No literature is available concerning production of this crop in the United States.

To evaluate feasibility of producing this crop in New England, information is needed on a wide array of cultural practices such a cultivar selection, secondary rowcover use in high tunnels, use of mulched beds, plant spacing, and planting date. In this study we sought to evaluate current cultivars available in England to determine comparative yields in an unheated 9.1m x 18.2m unheated high tunnel in Durham, NH. In addition, use of secondary rowcovers within the tunnel was examined for effect on yield, duration of harvest, and the number of days to harvest. Our third objective was to characterize the effect of row location (edge versus interior) on the response variables in the unheated high tunnel.

Methods

Varieties/Germplasm

Winter sprouting broccoli cultivars were sown and cultivated over two years in Durham, NH, from 2008 to 2010, for evaluation as a marketable spring crop. Five purple WSB and five white WSB cultivars, and one green annual broccoli cultivar as a control were compared (Table 7). Cultivars were obtained from Elsoms Seed Ltd. (Spalding, Lincolnshire, United Kingdom), Johnny's Selected Seeds (Winslow, ME, USA), and Thompson and Morgan (Lawrenceburg, IN, USA). Cultivars were selected for their ability to overwinter in temperate climates and provide a spring harvest, except for the cultivar DeCicco that is typically grown as an annual cultivar.

An experiment was also conducted to test the effects of uncovered, one or two layers of 42.2 $g \cdot m^{-2}$ (1.25 $oz \cdot y^{-2}$) Typar® rowcover (Autoverters, Inc., Roanoke Rapids, NC, supplier; hereafter referred to as "Typar"; also known as Dupont 5131) within the high tunnel. During the 2008-2009 growing season, six cultivars (Bordeaux, Claret, Red Head, Red Spear, Santee, DeCicco) were grown with either a Typar rowcover treatment or without a rowcover treatment. Uncovered plants were cultivated and harvested identically to covered treatments. During the 2009-2010 winter growing season, two cultivars (Santee, White Sprouting Early) were grown under one and two layers of Typar rowcover. These cultivars were also used to test for an edge effect in the 9.1 m x 18.2 m high tunnel.

Production Methods

Experiments were conducted in a 9.1m x 18.2m (30ft x 90ft) gothic design unheated high tunnel with 152 μm plastic (four year rating, Klerk's Plastic Products Manufacturing, Richburg, SC), manual roll-up sides, and automatic ventilation fans. Ventilation fans were set to open when the tunnel air temperature exceeded 18°C (65°F) in 2008/2009 and in 2009/2010 were set to open when air temperature exceeded 15.5°C (60°F). Seven 45 cm (18 in) wide unmulched raised beds were formed lengthwise in the high tunnel each season on 122 cm (4 ft) centers. Trickle irrigation was supplied to each row connected to a header and a frost-free hydrant. Based on soil tests, 14 kg (31 pounds) of Pro-Grow 5-3-4 (North Country Organics, Bradford, VT) and 37 kg (83 pounds) of lime were applied to the tunnel prior to bed preparation.

Plants were seeded 2 Sept. 2008 for a spring 2009 harvest and 19 Aug. 2009 for a spring 2010 harvest (Table 8). Seeds were germinated in a climate controlled greenhouse and seedlings were transplanted four weeks later into a staggered double row on raised beds with 23 cm between rows and 38 cm between plants within a row. After transplanting, plants were watered on an as-needed basis through the fall and beds were hand-weeded as needed throughout the fall. Dipel (Valent Biosciences Corporation, Libertyville, IL) foliar applications of *Bacillus thuringiensis* were applied at label rates to control caterpillars each fall.

Typar rowcovers were applied to plant beds when nighttime temperatures consistently fell below freezing using wire hoops and wooden stakes to elevate the rowcover from the plant canopy. Rowcovers remained in place through the winter season until harvest. Rowcovers were removed when harvest began in mid-March. Marketable shoots were harvested and weighed during the months of March, April, and May.

Experimental Designs

The cultivar experiment design was completely random with four replications of nine cultivars with experimental units of seven plants. The cultivar experiment was repeated in 2008-2009 and 2009-2010. Rowcover experiments were also conducted while the cultivar experiment was in progress, but were independent of the cultivar experiment. During the 2008-2009 growing season, six cultivars were grown with and without a rowcover treatment. During the 2009-2010 winter growing season, two cultivars were grown with either a single layer or a double layer of rowcover and either in an edge row or interior row. The rowcover experiments were completely random with four replications and experimental units of seven plants.

Data Collection and Analysis

Marketable shoots were harvested during the months of March, April and May. Harvested shoots ranged from approximately 10 cm to 20 cm in length and bore compact heads with unopened differentiating buds. Primary heads, which had shorter stems and measured up to 10 cm across, were also harvested and combined with lateral shoots. Lateral stems were handpicked close to the main stem of the plant and lateral stems that did not snap off easily by hand were considered too tough and therefore unmarketable. Leaves were left on the stem for consumption with the whole shoot. All plants were harvested at least once and additional harvests were possible from tertiary shoots out of leaf axils on secondary shoots below the harvest point. Total yield was recorded for each experimental unit of seven plants and the number of plants per plot that produced shoots at each harvest was counted. Plants were harvested twice per week.

Data were analyzed by Analysis of Variance (ANOVA) in JMP 8 (SAS Institute, 2009). Significant differences between treatments were assessed using Tukey's HSD tests ($p<0.05$). Data were collected from each plot for the following dependent variables: yield (grams per plant), harvest duration (time elapsed from first harvest to final harvest), and time elapsed from seed sowing to first harvest (days to harvest). Multivariate correlation analysis was used to evaluate relationships between the dependent variables.

Plant mortality was recorded each season (on a plant-by-plant basis) at the start of each year's harvest. Results and analysis are based on experimental units of seven plants; this caused reported yields to be slightly lower than if average yields were calculated on surviving plants only. An ANOVA tested for differences between the data sets comparing means based on experimental units of seven plants and means that accounted for a loss of plants. No significant difference between analytical methods and no interaction between cultivar and analysis method was detected in the test results ($p<0.05$).

Results and Discussion

Cultivar Experiment

Few significant differences were evident in individual analyses of each seasons' data; the only differences detected in 2009 were between the highest and lowest yielding cultivar and no significant differences were detected in 2010 despite clearly significant differences attributed to variety in the overall ANOVA. Overall, the two lowest yielding cultivars, Claret and Red Head, were significantly different from the four highest yielding cultivars (Burbank, White Sprouting Early, Late White Star, Red Spear). However, trends were visible in both seasons that showed some cultivars consistently yielding higher than others. White-sprouting cultivars yielded higher than purple sprouting cultivars overall in a least square means contrast test (p=0.002).

In general, yields were higher in 2009 than in 2010, with the exception of White Sprouting Early, Santee, and Red Head. While all plants survived in 2009-2010[2], some plants experienced mortality in 2008-2009 (Table 9). Seasonal deviations in yield were least pronounced in the two lowest yielding cultivars, Claret and Red Head, in addition to the higher yielding—but not significantly different—cultivars Burbank and Late White Star (Table 10). The greatest deviation in the overall means occurred in the cultivars White Sprouting Early, Colusa, and Red Spear, which were also the three highest yielding cultivars after two seasons. In White Sprouting Early and Red Spear, the seasonal means deviated from the overall mean by as much as 22 percent and 21 percent, respectively, with each yielding higher in 2009 than in 2010.

Time elapsed from seed to harvest varied, dependent on both year and cultivar (Table 11). Mean growth period in 2009 was 208.4 days and in 2010 was 233.8. This is a 25-day difference that may be due in part to the 13-day difference in planting dates between seasons in addition to natural seasonal variations of temperature and sunlight. Most cultivars were harvested between twelve and seventeen days later in 2010 than in 2009 with the exception of Ninestar (22.5 days later) and Santee (8.7 days later). The trends between cultivars remained constant each year in regards to those cultivars that showed longer days to harvest and those that showed shorter days to harvest. In both seasons, the cultivars Claret, Late White Star, and Ninestar required the longest interval

[2] The only exception was a loss of five plants in one block of the cultivar Santee that died shortly after transplanting leaving only two healthy plants at the start of winter.

from seed to harvest maturity and the cultivars White Sprouting Early, Santee, and Red Spear required the shortest interval from seed to harvest. As a group, white-sprouting cultivars required more time to reach harvest maturity than purple-sprouting cultivars ($p<0.05$).

Duration of harvest was influenced by an interaction between year and cultivar ($p<0.05$). The range in harvest duration was 21.5 to 40.7 days with a standard error of 2.9. Most cultivars had similar harvest duration in both years while two (Red Spear and WSE) were harvested for a significantly shorter period of time in 2010 than in 2009 (Figure 11). A multivariate correlation analysis between harvest duration and time from seed to harvest was negative in 2009 and highly significant both years (Table 12). The correlation analysis combining both years was weaker, but the trend suggests that as the number of days from seed to harvest increases, the harvest period shortens. The correlation between harvest duration to yield and the correlation between days from seed to yield were weak.

Rowcover Experiment

Rowcovers significantly reduced plant mortality for all varieties tested in 2008-2009, the only year that mortality was observed (Figure 12). Uncovered plots experienced a mean mortality rate of 57 percent and covered plants experienced a mean mortality of 10 percent. A single rowcover significantly increased per plant yield (206.5 grams per plant and 60.4 grams per plant, respectively. Uncovered plants required more days from seed to harvest (218.7) than covered plants required (202.0).

The rowcover experiment in 2010 tested for effects due to rowcover and rowcover location in the high tunnel. A rowcover effect was present in the yield analysis (Table

13). Mean yield from plants under a double layer of rowcover was 19 percent higher than the mean yield under a single layer. Harvest was slightly earlier (3 days) in the plots under two layers of rowcover than in those with a single layer, however, this difference was minimally statistically significant (Table 13). Harvest duration was influenced by an interaction of cultivar and rowcover treatment. Only one of the two cultivars (WSE) showed a statistically significant effect ($p<0.05$) due to rowcover application. Average harvest duration under two layers of rowcover was 35.4 days and only 23.8 days under a single layer of rowcover. An interaction was present between cultivar and row location in the edge row experiment (Table 14). A row location effect was only observed in one of two cultivars (Santee) as interior plots yielded 35 percent higher than edge plots. Santee may be more susceptible to cooler temperatures and to more extreme temperature fluctuations that occurred on edge row plots. Additional tests with more cultivars would lend more support and information to accurately describe this effect.

Plant Characteristics

Marketable spears ranged from approximately 8 cm to 25 cm, with most between 13 cm to 20 cm (Figure 13). Spears were harvested before buds began to enlarge and open. Secondary shoots (arising from the primary stem) gave rise to tertiary shoots at leaf nodes. These tertiary shoots were generally smaller, but harvestable 3-4 days after the secondary shoots were cut. Most shoots were tender and readily snapped off by hand at harvest, however some shoots were tough and stringy, and therefore considered unmarketable. The lower portion of the spear closest to the main stem was first to develop tough tissues. The cultivar Claret exhibited tough tissues throughout its spears, resulting in low yields in the cultivar trial.

Purple-sprouting broccoli inflorescences were shades of purple and white-sprouting cultivars ranged from white (White Sprouting Early, Figure 14) to a creamy yellow (Colusa, Figure 16) and pale green. The cultivar Burbank (Figure 17) exhibited pale yellow heads with a purpling tint that developed as the head matured, which gave the undesirable impression of necrosis in the inflorescence. This was also present to a lesser degree in Colusa, but was generally absent from the cultivars White Sprouting Early, Ninestar, and Late White Star.

Characteristics such as plant height and leaf shape varied within and between cultivars. Some harvested spears consisted primarily of long stems with an inflorescence and very few leaves (Figure 13), while others had several leaf nodes (Figure 14, Figure 15, Figure 16, and Figure 17). The leaves of marketable shoots were tender and edible and therefore considered part of the marketable product. Purple-sprouting broccoli inflorescences were similar in shape and texture, composed of soft differentiating buds (Red Spear, Figure 15 and Figure 20; Santee, Figure 13). Inflorescences on white-sprouting cultivars frequently were smaller in diameter than on purple-sprouting cultivars; and, while some had differentiating buds (White Sprouting Early, Figure 14 and Figure 19; Colusa, Figure 16) others consisted of undifferentiated curds (Burbank, Figure 17; Ninestar, Figure 18; Late Sprouting Early).

Stem and petiole splitting was widespread throughout most cultivars in 2008-2009 (Figure 21), but minimal stem splitting occurred in 2010. The cause of this injury is unknown, but it may have been related to increased plant vigor and freezing and thawing of water in the plant stems throughout the winter. Effects of splitting on plant yield were not specifically determined, but it did not appear to be detrimental. Visual observations indicated that splitting was equally present on uncovered and covered plants. Necrosis and chlorosis were observed in both seasons, especially on the oldest leaves of all cultivars, including cultivars under rowcover (Figure 23). The cause appeared to be freeze injury to the leaf lamina consistent with previous observations (Tan, Wearing et al., 1999). In general, freeze injury was less severe under covered compared to uncovered plants and was not present on new spring growth. In 2010, visual observation indicated somewhat less freeze damage under two layers than under a single layer of rowcover, but this affect was not quantitatively measured. Contact with rowcover likely exacerbated freeze injury to plant tissue due to a more rapid rate of freezing at the rowcover surface compared to the interior (Waggoner 1958, as cited in (Wells and Loy, 1985).

Necrotic leaf margins and necrotic spear tips were observed in some varieties. This condition was noticeable on the cultivars Burbank (Figure 22), Colusa, and White Sprouting Early, resulting in unmarketable spears. Possible causes include freeze damage due to direct contact with a rowcover, however many damaged tissues were not in contact with rowcover and did not appear to show a water-soaked appearance. Other possible factors include a nutrient deficiency or possible heat damage during the warmer spring days.

Plant lodging was widespread in the experiment. Lodging was characterized by plant stems that failed to support plant weight and grew on their "side" extending horizontally along the ground before curving up. Factors that may have contributed to plant lodging were raising transplants in an excessively warm greenhouse and insufficient "hardening off" prior to transplanting. In both 2008 and 2009, broccoli transplants were moved directly from the greenhouse and transplanted into the high tunnel. In an unrelated experiment, broccoli transplants that were allowed to acclimate to cool temperatures prior to planting in an outdoor environment were less susceptible to lodging (unpublished data). Effects of plant lodging on yield of winter sprouting broccoli is unknown, but it is possible that reducing lodging would increase yields.

Internode length varied during the experiment and plants within the same experimental unit exhibited visible differences. Occasional plants showed shortened internodes that contributed to a compact bush-like appearance that occasionally led to difficulty with harvest because leaves and spears were tightly compact compared to more "open" plants. Despite this, the number of marketable spears appeared to be greater in some cases. Further investigation is required to adequately describe the effect of internode length on yield and marketability. It is not clear whether this is due to genetic or environmental factors. In another experiment, plants that entered the winter months as very young transplants exhibited compact characteristics with short internode lengths and very little freeze injury (unpublished data).

Summary

The results of this study indicated that rowcover applications should be used for overwintering winter sprouting broccoli in unheated high tunnels. However, this study does not address the costs and benefits of removing rowcover in periods of warmer temperatures and sunlight. A temperature experiment (see Chapter 2) suggested that two layers of Typar rowcover buffer extreme temperature fluctuations, but was slower to gain heat on cloudy days and when temperatures rose at night. Two layers of rowcover also filter out more light than one layer, but can offer increased insulation to prevent heat from escaping. The results of this study suggest that using a second layer of Typar rowcover may provide a slight increase in yield over one layer of Typar rowcover; however, the scope of the study did not include other rowcover types and combinations of applications. While using a single layer of Typar clearly increases plant yields over uncovered plants, the gains of using a second layer of Typar are unclear. Using a second layer of Typar may also incur higher labor costs if it is periodically removed to allow greater light penetration and put back in place to retain heat.

The results of the cultivar experiment and anecdotal observations suggest that some cultivars are more suited to winter production in unheated high tunnels than others. Santee, Red Spear, White Sprouting Early were among the highest yielding and exhibited desirable physical characteristics. Primarily, their harvested spears were attractive, tender, early maturing, and ideal length. Claret and Red Head were low yielding while Colusa and Burbank exhibited potential yield but were susceptible to undesirable bud coloring and tissue damage. Late White Star offers potential to lengthen the duration of harvest as a later-maturing cultivar but likely cannot compete with the financial returns offered by other crops if it encroaches on the spring planting schedule. These experiments confirmed that fall plantings of winter sprouting broccoli may be overwintered in an unheated high tunnel for a spring harvest in New Hampshire.

Tables

Table 7. Cultivars and cultural treatments developed in England used in a two-year study conducted in a 9.1 m x 18.2 m high tunnel at UNH Woodman Farm.

Cultivar	Seed Source	Supplier Recommendations: Planting	Supplier Recommendations: Harvest	2009 Cultivar Exp.	2009 Rowcover Exp.	2010 Cultivar Exp.	2010 Rowcover Exp.
Purple biennial							
Bordeaux	Elsoms Seeds Ltd.[x]	April thru mid-August	Feb. thru March; June thru early Nov.	X	X		
Claret	"	Early August	Mid-Mar. thru mid-May	X	X	X	
Red Head	"	Early August	Mid-Mar. thru mid-May	X	X	X	
Red Spear	"	Early August	March thru mid-May	X	X	X	
Santee (BE 2778)	"	April thru mid-August	Feb. thru March; June thru early Nov.	X	X	X	X
White biennial							
Burbank	Elsoms Seeds Ltd.	Early August	Mid-Feb. thru mid-Apr.	X		X	
Colusa	"	Early August		X		X	
Late White Star (LWS)	"	Early August	Mid-Mar. thru mid-May	X		X	
Ninestar (9 Star)	T & M[w]			X		X	
White Sprouting Early (WSE)	"	Early August	March thru mid-may	X		X	X
Green annual							
Decicco	JSS[v]			X	X		

[z]Elsoms Seeds 2008 Sprouting Broccoli Fact Sheet. Recommendations developed for growing conditions in England.
[x]Elsoms Seeds Ltd., Spalding, Lincolnshire, UK.
[w]Thompson and Morgan Seedsmen, Inc., Lawrenceburg, IN
[v]Johnny's Selected Seeds, Winslow, ME

Table 8. Abbreviated timeline of activities during a two-year winter-sprouting broccoli cultivar trial at UNH Woodman Farm.

Activity	2008-2009	2009-2010
Seed	September 2, 2008	August 18, 2009
Transplant	October 1, 2008	September 18, 2009
Apply Rowcover	November 21, 2008	November 18, 2009
Remove Rowcover	March 11, 2009	March 6, 2010
Harvest	March 12, 2009	March 6, 2010

Table 9. Mortality in the 2008-2009 cultivar trial.

	Plot Mean (7 plants)		Per Plant Mean (7 plants - # dead plants)		
Cultivar	Mean Total Harvest Weight (g)	Tukey's Test (α<0.05)	Mean Total Harvest Weight (g)	Percent Mortality	|Plot Mean - Plant Mean|
White Sprouting Early	328.357	a	328.357	0%	0.000
Red Spear	292.929	ab	292.929	0%	0.000
Colusa	292.786	ab	309.929	4%	17.143
Burbank	277.214	ab	288.179	4%	10.964
Late White Star	261.214	ab	271.571	4%	10.357
Ninestar	238.464	ab	238.464	0%	0.000
BE2778	224.929	ab	249.405	11%	24.476
DeCicco	213.143	ab	225.829	7%	12.686
Bordeaux	186.179	ab	203.114	11%	16.936
Claret	170.643	ab	191.860	11%	21.217
Red Head	151.286	b	197.869	21%	46.583
Statistical Analysis					
ANOVA Probabilities	0.018		0.114		
Standard Error	34.757		35.838		

Table 10. Yield (grams) of winter sprouting broccoli in 2009 and 2010.

		2009		2010		2009-2010		
Cultivar	Color	Mean	Tukey's Test (α<0.05)	Mean	Tukey's Test (α<0.05)	Mean	Tukey's Test (α<0.05)	Yearly Deviation From the Mean (+/-)
Burbank	White	277.2	ab	276.9	a	277.1	a	0.1
White Sprouting Early	White	328.4	a	214.7	a	271.5	a	56.8
Late White Star	White	261.2	ab	273.1	a	267.1	a	5.9
Red Spear	Purple	292.9	ab	232.3	a	262.6	a	30.3
Santee	Purple	224.9	ab	272.4	a	248.7	ab	23.7
Colusa	White	292.8	ab	188.4	a	240.6	ab	52.2
Ninestar	White	238.5	ab	207.9	a	223.2	ab	15.3
Claret	Purple	170.6	ab	153.5	a	162.1	b	8.6
Red Head	Purple	151.3	b	161.5	a	156.4	b	5.1
DeCicco	Green	213.1	ab	--		--		
Bordeaux	Purple	186.2	ab	--		--		
Standard Error		34.8		27.1		21.8		
Year Mean		248.6		220.1				
ANOVA Probabilities								
Cultivar		0.0179		0.1136		0.0004		
Year		--		--		0.0547		
Cultivar*Year		--		--		0.1569		
Contrast White to Purple		0.0019		0.1450		0.0017		

Table 11. Days from seed to harvest of winter sprouting cultivars in 2008-2009 and 2009-2010.

		2008-2009		2009-2010		2008-2010		
Cultivar	Color	Mean	Tukey's Test ($\alpha<0.05$)	Mean	Tukey's Test ($\alpha<0.05$)	Mean	Tukey's Test ($\alpha<0.05$)	Yearly Deviation From the Mean (+/-)
Ninestar	White	216.0	a	238.5	a	227.3	a	11.3
Late White Star	White	216.8	a	232.5	ab	224.6	ab	7.8
Claret	Purple	217.0	a	229.0	bc	223.0	abc	6.0
Burbank	White	208.3	ab	226.0	bcd	217.1	bcd	8.8
Red-Head	Purple	208.5	ab	223.5	cd	216.0	cd	7.5
Colusa	White	206.3	ab	222.5	cd	214.4	de	8.1
White Sprouting Early	White	202.8	abc	220.0	de	211.4	def	8.6
Red Spear	Purple	199.8	bc	213.5	ef	206.6	ef	6.8
Santee	Purple	200.3	bc	209.0	f	204.6	f	4.3
Bordeaux	Purple	196.5	bc					
DeCicco	Green	190.0	c					
Standard Error		3.2		1.543		1.8		
Year		208.4		223.8				
ANOVA Probabilities								
Cultivar		0.0001		0.0001		0.0001		
Year		--		--		0.0001		
Cultivar*Year		--		--		0.3398		
Contrast White to Purple		0.0086		0.0000		0.0000		

Table 12. Pairwise correlation coefficients from multivariate analysis of yield, harvest duration, and days from planting of winter sprouting broccoli.

Variable	Variable	2009	2010	2009-2010
Yield	Days from Planting	-0.2571	-0.1730	-0.3752
		(p=0.0921)	(p=0.3129)	(p=0.0012**)
Yield	Harvest Duration	0.3716	0.3470	0.4598
		(p=0.0130*)	(p=0.0382*)	(p<0.0001**)
Days from Seeding	Harvest Duration	-0.9194	-0.4393	-0.6885
		(p<0.0001**)	(p=0.0074**)	(p<0.0001**)

*p<0.05
**p<0.01

Table 13. Effects of rowcovers on yield and days to harvest in an unheated high tunnel in 2010 in Durham, NH.

Effect Test	Rowcover Application	Mean	Standard Error	p-value (p<0.05)
Yield (grams per plant)	Double	262.9	16.4	0.0417
	Single	213.0	16.4	
Elapsed time from seed to harvest (days)	Double	198.5	0.9	0.0538
	Single	201.1	0.9	

Table 14. Effect of cultivar and row location on yield of winter sprouting broccoli grown in winter 2010 in an unheated high tunnel in Durham, NH.

Cultivar	Row Location	Mean	Standard Error	Significant Differences (Tukey's HSD)
Santee	Interior	282.0	23.2	a
Santee	Edge	183.9	23.2	b
WSE	Interior	233.6	23.2	ab
WSE	Edge	252.4	23.2	ab

Figures

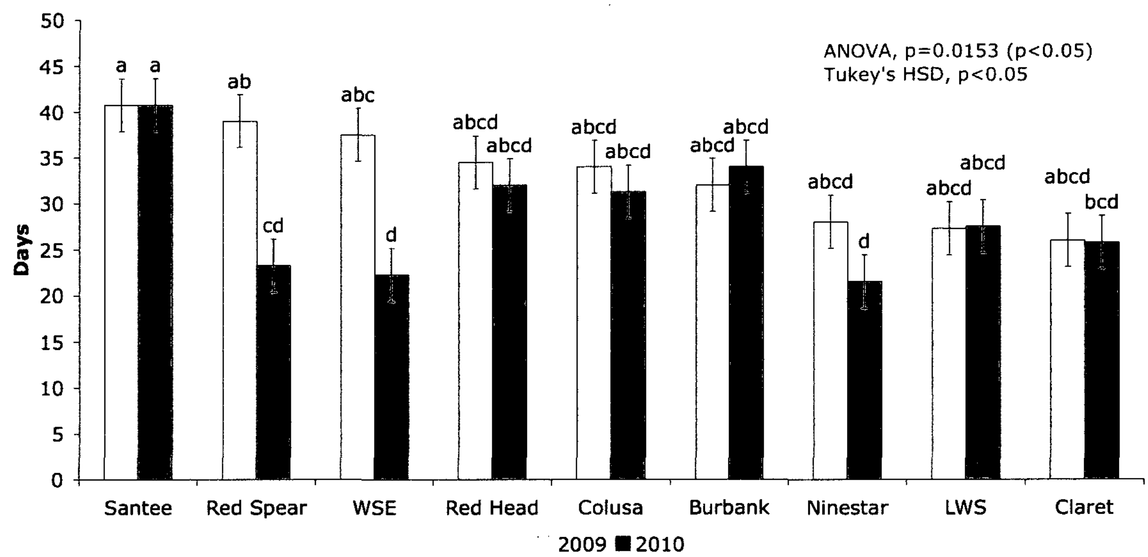

Figure 11. Duration of harvest of nine cultivars of winter sprouting broccoli harvested in spring 2009 and spring 2010 in Durham, NH.

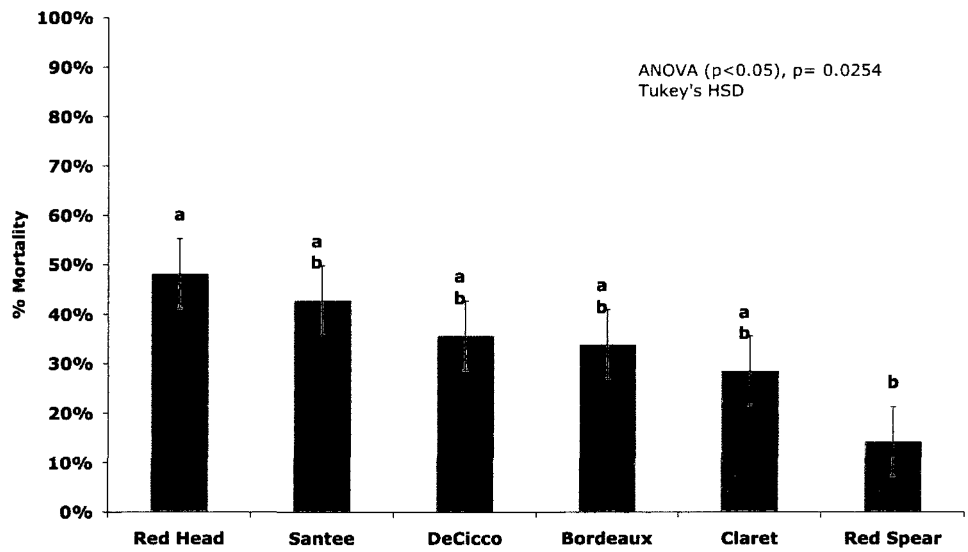

Figure 12. Comparison of cultivar on mortality of uncovered winter sprouting broccoli plants grown in an unheated high tunnel in 2008-2009 in Durham, NH.

Figure 13. Harvested spears of cultivar Santee (18 Mar. 2010).

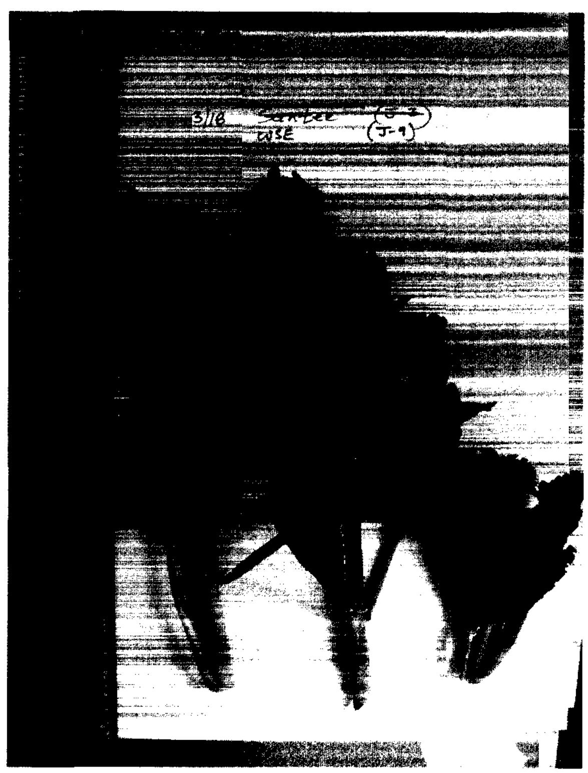

Figure 14. Harvested spears of cultivar White Sprouting Early (18 Mar. 2010).

Figure 15. Harvested spears of cultivar Red Spear (18 Mar. 2010).

Figure 16. Harvested spears of cultivar Colusa (26 Mar. 2010).

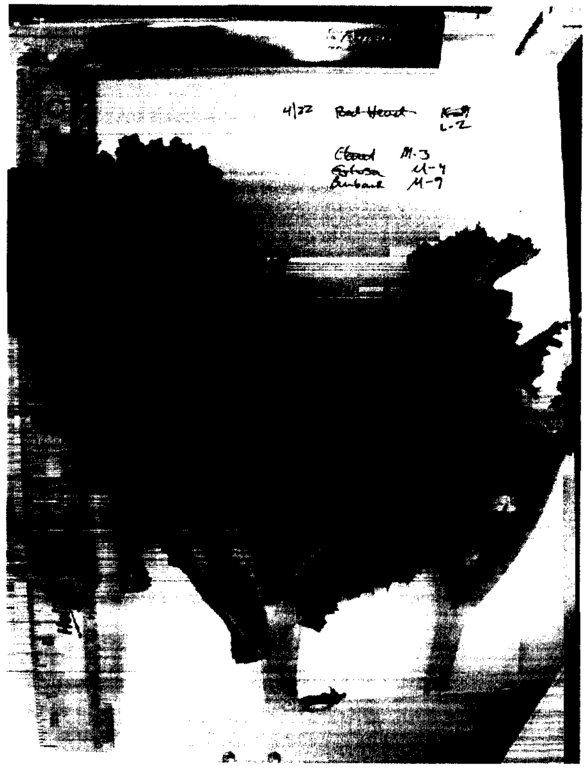

Figure 17. Harvested spears of the cultivar Burbank (2 Apr. 2010).

Figure 18. Top view of the cultivar Ninestar (27 Apr. 2009).

Figure 19. Top view of a mature White Sprouting Early plant (1 Apr. 2010).

Figure 20. Mature Red Spear plant (1 Apr. 2010).

Figure 21. Stem splitting on purple sprouting broccoli (26 Feb. 2009).

Figure 22. Necrotic damage at the tip of a spear and leaf margins on the cultivar Burbank (30 Apr. 2009).

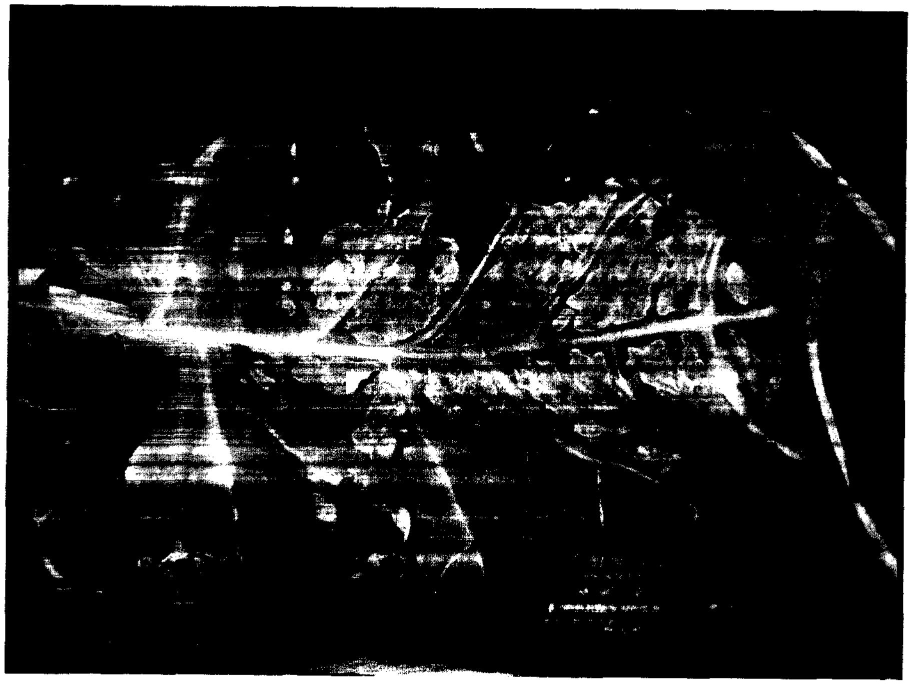

Figure 23. Damaged winter sprouting broccoli plant tissues (10 Apr. 2009).

CHAPTER IV

THE EFFECT OF PLANTING DATE ON YIELD OF WINTER SPROUTING BROCCOLI

Introduction

The effects of altering fall planting date on survival and yields of winter sprouting broccoli in New England are currently unknown. Competition for high tunnel space during the main cropping season dictates that winter sprouting broccoli should be planted in the fall while growers maximize their returns on higher value crops in the summer. In previous research at UNH Woodman Farm, planting dates were from August to the end of September. The ideal plant date should account for the space needs of the proceeding crop and allow time for sufficient growth to take place before the coldest winter months begin. It is advantageous to maximize plant size before the spring growing season, requiring plants to be well established in the fall. This preliminary study examined the effects of planting date on yield of winter sprouting broccoli in 4.3 m by 11.0 m (14 ft x 36 ft) unheated high tunnels in Durham, NH. The main objective was to identify a planting date window that would maximize yield of winter sprouting broccoli during the spring harvest.

Methods

Three cultivars (Bordeaux, Claret, Late White Star) were planted in 2008 in three 4.3 m by 11.0 m unheated high tunnels for a spring 2009 harvest. Each tunnel was an unventilated Quonset design with 152 μm 4-year greenhouse plastic and manual roll-up sides. Three seeding dates (19 Aug., 2 Sept, 16 Sept.) were selected and transplanting occurred one month after seeding. One high tunnel was used per planting date and the three cultivars were randomly distributed in each tunnel and grown under one layer of Typar[3] rowcover. High tunnels were managed equally to minimize any effect due to tunnel selection. Three 45 cm (18 in) wide unmulched raised beds were formed lengthwise in the high tunnel on 122 cm (4 ft) centers. Irrigation was supplied by trickle irrigation in each row connected to a header and a frost-free hydrant.

Three new cultivars (Santee, Burbank, Red Spear) were selected in 2009 to repeat the planting date experiment for harvest in 2010. The cultivar Bordeaux was no longer available and Claret and Late White Star were outperformed by the newly selected cultivars in a cultivar experiment harvested in 2009. Treatments included one layer of Typar rowcover and uncovered plots and three planting dates (15 July, 12 Aug., 11 Sept.). All treatments were spread evenly across the three high tunnels in a randomized complete block design.

Results and Discussion

Yields of winter sprouting broccoli were higher in the earliest planting date as compared to the latest planting date in 2008/2009 (Table 15; Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, and Figure 29). The highest average yield of Bordeaux and Claret were recorded with the second planting date (2 Sep. 2008) and the highest yield of Late White Star was recorded with the first planting date (19 Aug. 2008). Average yields

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[3] Typar®, 42.2 $g \cdot m^{-2}$ (1.25 $oz \cdot y^{-2}$) spundbonded rowcover; Autoverters, Inc., Roanoke Rapids, NC, supplier; hereafter referred to as "Typar"; also known as Dupont 5131

were lowest for all cultivars grown on the latest planting date. Of the three cultivars grown in the experiment, the highest average yield was recorded from Late White Star.

The shortest harvest duration was recorded with the latest planting date. Average harvest duration was similar for the first two planting dates for the cultivars Late White Star and Claret. The cultivar Bordeaux had consistent harvest duration for all three planting dates ranging from 41.0 days to 43.5 days. Recorded days from seed to harvest of the first and last planting dates were equal while the recorded average for the second planting date was slightly higher. The cultivar Bordeaux required the fewest days from seed to harvest compared to Claret and Late White Star. The average date of first harvest for the cultivar Bordeaux was similar across all three planting dates. The latest dates of first harvest for Late White Star and Claret were recorded on the last planting date.

Mortality was a major factor in the results of the 2010 harvest and yield data were not collected (Figure 30). In addition, the planned final planting date cohort was never planted because of the vigorous growth and robust plants of the first planting that would have shielded the youngest plants from sunlight. There was a significant interaction between rowcover and cultivar for mortality. The cultivar Burbank experienced 61.9 percent survival under rowcovers and 9.5 percent survival outside rowcovers. The cultivars Red Spear and Santee ranged in average survival from 9.5 percent to 21.4 percent. Planting date did not significantly affect mortality; an average of 6.0 plants died in the first planting and 4.9 in the third. Rowcover provided a 1.6°C increase in average temperature compared to uncovered air temperature with differences occurring only at night (Figure 31, Table 16).

The results from the 2009 harvest season indicate that mid-August to early-September was an ideal planting window for New Hampshire, but only in comparison to the mid-September planting date. The results from 2010 suggest that planting prior to mid-August may be detrimental by allowing plants to develop beyond a suitable maturity for overwinter survival. In 2010, plants were very large for July and August planting dates, but especially for the 15 July planting (Figure 32, Figure 33, Figure 34, Figure 35). Lateral spears were already developing at the time of rowcover application. Though still high, the mortality recorded for the 12 Aug. planting date was lower than the 15 July planting date.

Further work is needed to more accurately describe the effect of planting date on yield, however trends were evident in the experiment results. A mid-August to early-September planting date is likely important in combination with crop management so that plants can mature without growing exceedingly large. Some plants in Fall 2009 were nearly 150 cm in height, whereas observations from previous experiments suggest that 70-90 cm is ideal height (Figure 24, Figure 32).

Relative humidity may be an important factor to overall plant health in a winter growing environment. On most days through the winter, the 4.3 m by 11.0 m high tunnels were unventilated and this may have contributed to increased high humidity and subsequent exposure or infection with fungi that may have negatively impacted plants. In addition, unventilated tunnels were subject to more extreme temperature swings because of higher increases in temperature on sunny days. Although temperatures were coolest in 2008/2009 (Chapter 2), mortality was greatest in 2009/2010, suggesting that other factors may have contributed.

Tables

Table 15. Mean yield, harvest duration, days from seed to harvest, and date of first harvest for cultivars planted on three planting dates in 4.3 m by 11.0 m unheated high tunnels.

	19 Aug. 2008	2 Sept. 2008	16 Sept. 2008	Cultivar Total
		Yield (Grams per plant)[z]		
Bordeaux	77.3 ± 52.7	144.3 ± 37.2	72.3 ± 27.9	98.0 ± 50.2
LWS[y]	202.2 ± 43.4	177.8 ± 15.2	36.7 ± 17.5	148.2 ± 41.3
Claret	80.4 ± 118.5	116.4 ± 77.2	40.6 ± 11.4	79.1 ± 106.2
Date Total	146.2 ± 93.8	120.0 ± 52.5	51.0 ± 25.2	107.3 ± 74.4
		Harvest Duration (Days)		
Bordeaux	43.5 ± 7.6	43.5 ± 2.9	41.0 ± 7.3	42.7 ± 5.8
LWS	28.8 ± 7.5	26.0 ± 13.3	9.7 ± 6.8	22.5 ± 12.3
Claret	23.5 ± 12.5	33.8 ± 12.1	13.5 ± 5.5	23.6 ± 12.9
Date Total	29.8 ± 12.3	31.9 ± 12.1	22.5 ± 15.9	29.8 ± 14.1
		Days From Seed to Harvest		
Bordeaux	215.3 ± 13.3	201.5 ± 2.9	195.0 ± 6.3	203.9 ± 11.8
LWS	229.0 ± 6.2	228.0 ± 7.5	231.3 ± 5.2	229.3 ± 7.8
Claret	229.8 ± 8.0	217.5 ± 11.7	223.8 ± 5.5	223.7 ± 8.3
Date Total	215.7 ± 11.2	224.7 ± 13.6	215.4 ± 17.2	218.7 ± 14.4
		Date of First Harvest[x]		
Bordeaux	3/22 ± 13.3	3/22 ± 2.9	3/30 ± 6.3	3/24 ± 8.7
Late White Sta	4/5 ± 6.2	4/18 ± 7.5	5/5 ± 5.2	4/18 ± 11.9
Claret	4/5 ± 8.0	4/7 ± 11.7	4/27 ± 5.5	4/13 ± 15.0
Planting Date	4/5 ± 11.2	3/31 ± 13.6	4/19 ± 17.2	4/8 ± 15.8

[z]Mean ± standard deviation

[y]Late White Star

[x]Date (mm/dd) ± standard deviation (days)

Table 16. Temperatures (°C) in a 4.3 m x 11.0 m unheated high tunnel from 29-31 Jan. 2010.

	Rowcover Air	Tunnel Soil	Rowcover Soil	Tunnel Air
Average	-1.8	2.2	2.3	-3.4
Stdev	8.4	1.0	0.6	9.5
Min	-11.4	0.9	1.4	-13.7
Max	21.4	4.7	3.7	21.9

Figures

Figure 24. Winter sprouting broccoli planted on 19 Aug. 2008, and photographed on 20 Nov. 2008.

Figure 25. Winter sprouting broccoli planted on 19 Aug. 2008, and photographed on 12 Mar. 2009.

Figure 26. Winter sprouting broccoli planted on 2 Sept. 2008, and photographed on 20 Nov. 2008.

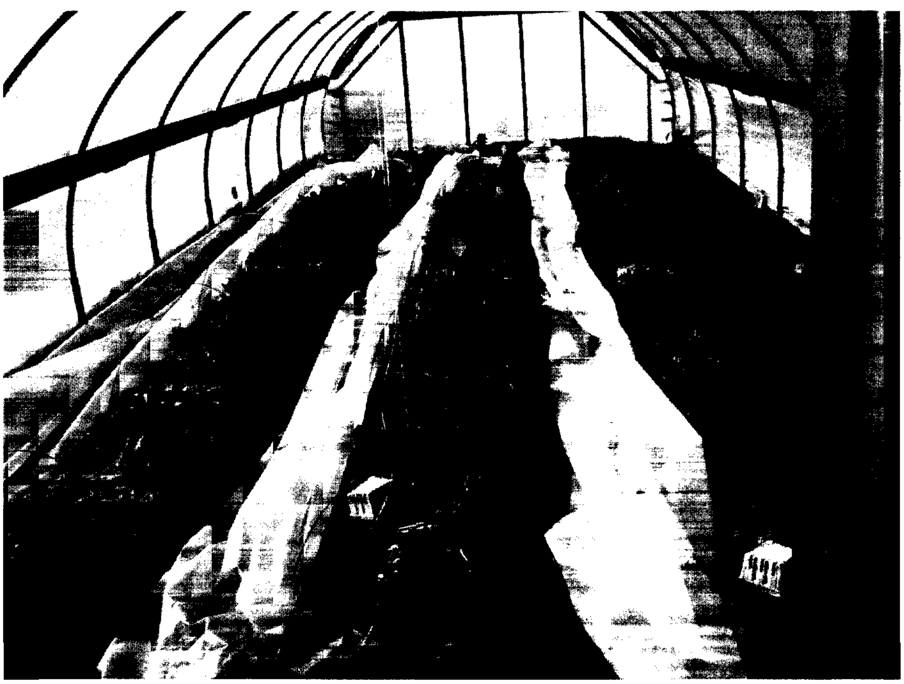

Figure 27. Winter sprouting broccoli planted on 2 Sept. 2008, and photographed on 12 Mar. 2009.

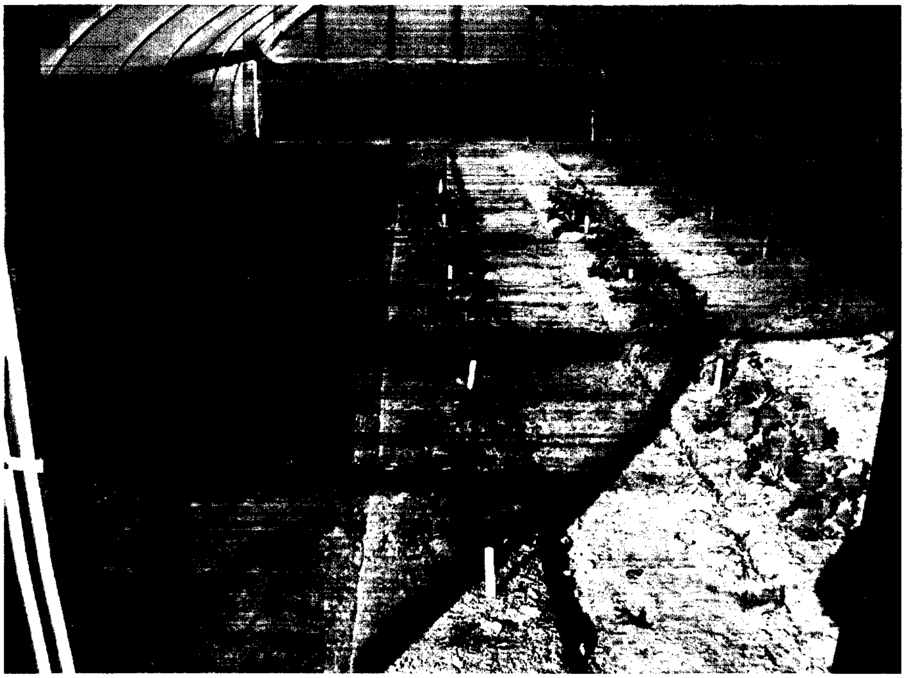

Figure 28. Winter sprouting broccoli planted on 16 Sept. 2008, and photographed on 20 Nov. 2008.

Figure 29. Winter sprouting broccoli planted on 16 Sept. 2008 and photographed on 12 Mar. 2009.

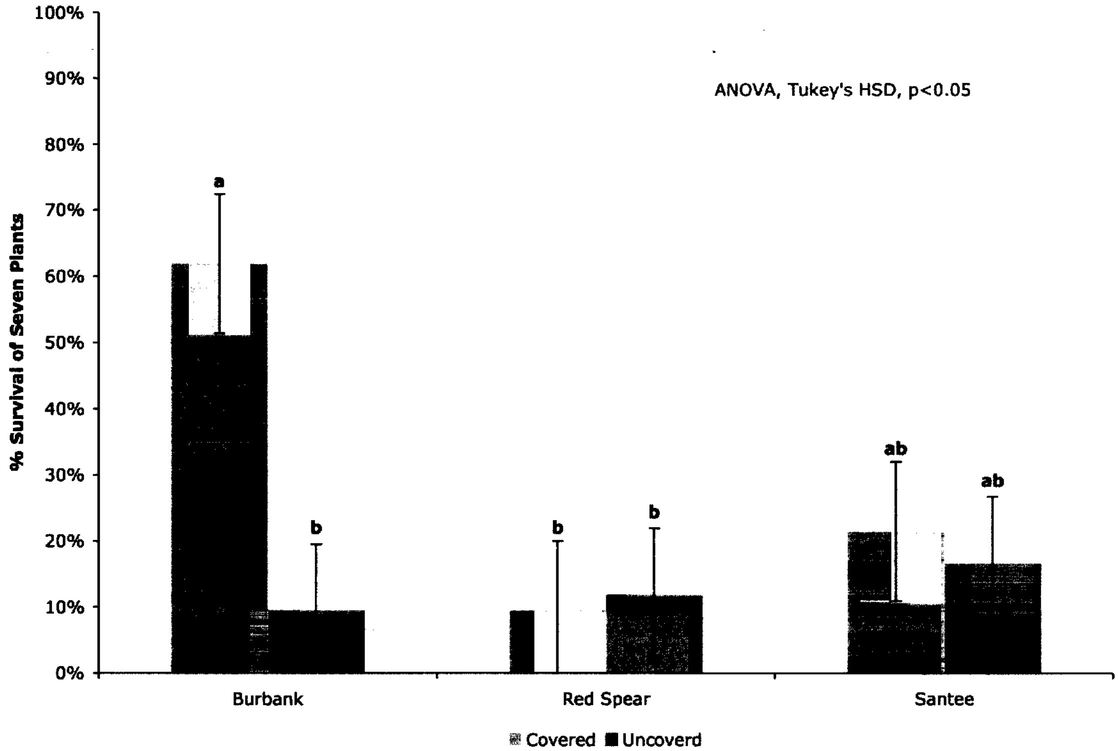

Figure 30. Mortality of three winter sprouting broccoli cultivars in 4.3 m by 11.0 m unheated high tunnels in 2010.

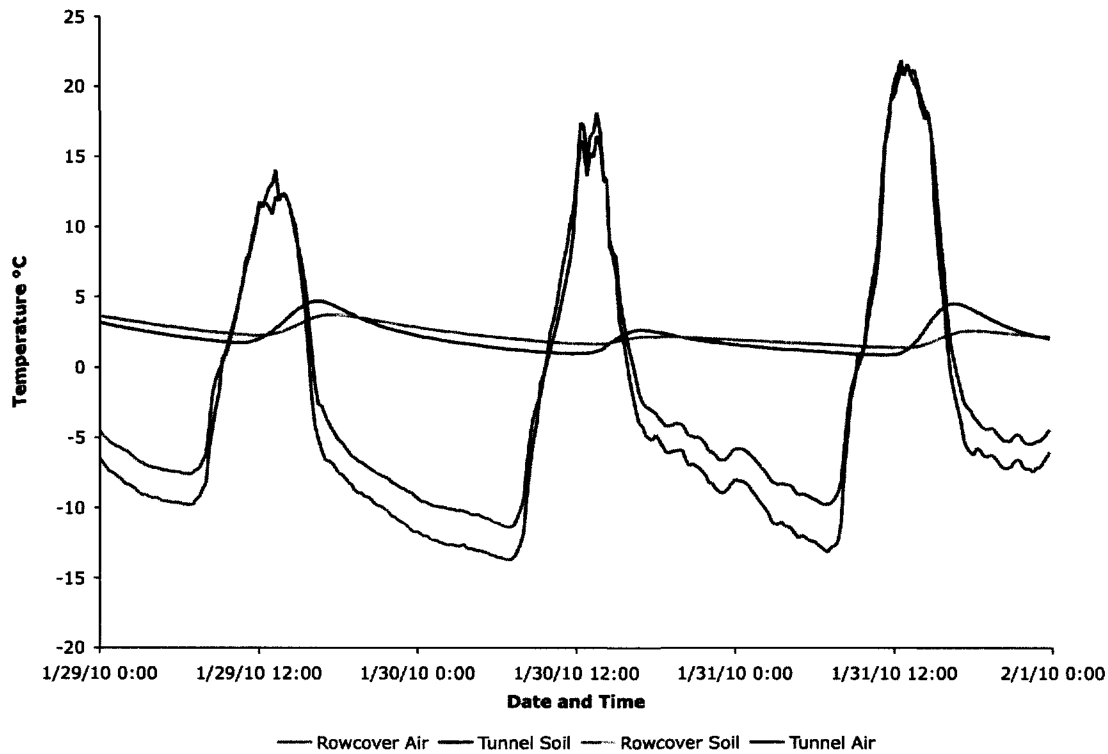

Figure 31. Air and soil temperature inside a 4.3 m x 11.0 m unheated high tunnel from 29-31 Jan. 2010.

Figure 32. Winter sprouting broccoli in a 4.3 m x 11.0 m unheated high tunnel on 20 Nov. 2009.

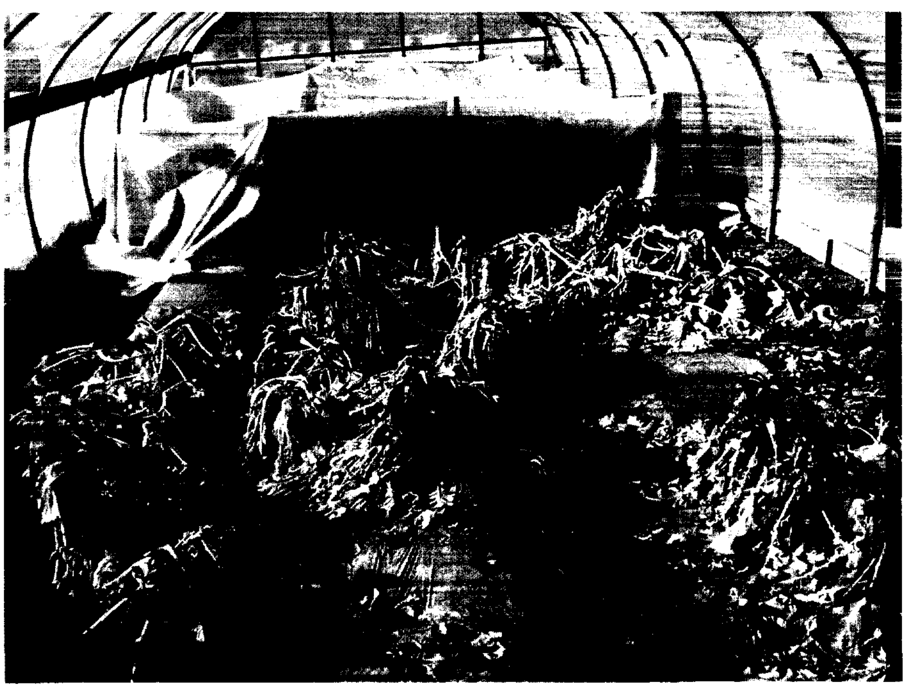

Figure 33. Winter sprouting broccoli in a 4.3 m x 11.0 m unheated high tunnel on 11 Feb. 2010.

Figure 34. Winter sprouting broccoli underneath one layer of Typar rowcover in an unheated 4.3 m by 11.0 m unheated high tunnel on 11 Feb. 2010.

Figure 35. Winter sprouting broccoli in an unheated 4.3 m by 11.0 m unheated high tunnel on 6 Mar. 2010.

CHAPTER V

EFFECT OF LOW TUNNEL ROWCOVERS ON TEMPERATURE, LIGHT, AND SURVIVAL OF WINTER SPROUTING BROCCOLI

Introduction

Winter production experiments for winter sprouting broccoli were conducted over three years in Durham, NH, in unheated high tunnels. Recently, use of low tunnels for winter production has gained greater public awareness as demonstrated by winter production tools actively marketed by Johnny's Selected Seeds (Winslow, ME) and descriptions of low tunnels by season extension pioneer Eliot Coleman and others (Blomgren and Frisch, 2007; Coleman, 2009). Potential advantages of low tunnel structures over high tunnel structures are low cost, simple assembly/disassembly, and mobility in rotations. There is, however, little direct discussion of low tunnels for overwintering crops in peer-reviewed literature.

This experiment was intended as a pilot project to study low tunnel environments at UNH Woodman Farm and to examine the viability of growing winter sprouting broccoli in those environments. Initial questions were:

- Which rowcover materials provide the greatest protection of winter sprouting broccoli in New England winters?
- How do different rowcover materials affect temperature and light transmission?

- What are the affects of different rowcover materials on survival of winter sprouting broccoli?

Materials and Methods

Eight 30.5 m (100 ft) rows with raised beds mulched with black plastic were prepared on 2.4 m (8 ft) centers with trickle irrigation (Table 17). Thirty-eight centimeter (15 in) sections of half-inch (1.27 cm) steel rebar were driven 25 cm into the soil on both sides of the raised bed and spaced 0.8 m apart down the length of each row and spaced approximately 0.5 m off center. Three meter sections of 0.5-inch (1.27 cm) schedule 40 PVC conduit were inserted over the rebar posts so that the conduit was buried 12-15 cm below the soil surface. Eight combinations of different types of rowcovers were applied over these conduit hoops with the exception of two rows that were supported by wire half hoops (Table 18).

The eight treatments were compared in a non-replicated study. Typar[4] rowcover was applied on 13 Oct. 2009, and perforated[5] or solid greenhouse plastic[6] applications were applied 20 Nov. 2009. Rowcovers were anchored along each edge and at the ends with field soil. Rowcovers remained in place throughout the winter season until 2 Apr. 2010. Severe wind followed by freezing weather and snow removed the plastic layer from row one and the harsh conditions prevented attempts to repair the application.

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[4] Typar®, 42.2 $g \cdot m^{-2}$ (1.25 $oz \cdot y^{-2}$) spundbonded rowcover; Autoverters, Inc., Roanoke Rapids, NC, supplier; hereafter referred to as "Typar"; also known as Dupont 5131

[5] Dubois Agrinovation, Saint-Remi, Quebec, Canada; 50 μm, 500 holes/m^2

[6] Sunmaster 152 μm Greenhouse Plastic, Farmtek Inc., Dyersville, IN.

However, the two remaining layers of Typar rowcover remained in place for the duration of the season.

Three cultivars of winter sprouting broccoli (White Sprouting Early, Santee, and Red Spear) were seeded in a greenhouse on 20 Aug. 2009, and transplanted one month later on 26 Sept. 2009, at 45 cm spacing on center of each row in blocks of six plants. Each of the eight rows was dedicated to one unreplicated rowcover treatment spanning the whole length.

Temperature and light monitoring was conducted using UA-002-08 HOBO Pendant data loggers (Onset Computer Corp, Bourne, MA). One logger was placed in each tunnel to record temperature and light under each rowcover regime. Light transmission was collected in lum/ft^2. Loggers were hung vertically by string from a bow in each tunnel. By equipment design, the optimum placement of the light sensor should be face-up in order to receive maximum light. In a replicated equipment test, light readings from vertically hung loggers received 40-50 percent of the light received to horizontally positioned loggers (unpublished). Although light transmission readings were likely underestimated in this experiment differences between rowcover applications could still be observed. Cumulative heat units were calculated from 20 Nov. 2009 to 2 Apr. 2010, and were calculated using the Baskerville-Emin method (Baskerville and Emin, 1968) at base 4.4°C (40°F) with no upper threshold cutoff. In the spring, all blocks were evaluated for survival and injury and mean survival was compared between rows.

Results and Discussion

Temperature and light results were analyzed for the coolest days of the year in order to describe the most extreme conditions encountered during the experiment. All rowcover applications transmitted similar amounts of light with the exception of a single cover of Typar covered with perforated plastic (Figure 36). The interpretation of the data is somewhat confounded because on all three days shown in the analysis, light readings were higher under the Typar/perforated plastic treatment than outdoors at 10:00 am. Higher light readings under the perforated plastic/Typar treatment than other treatments are to be expected because it is the thinnest plastic material and should allow more light transmission than the other treatments in the experiment. However, light received by uncovered light sensors should exceed light received by covered light sensors. One possible explanation is that the internal clock on the logger measuring outdoor light and temperature levels may have been offset by as much as two hours. The data sets were reviewed for discrepancies in the reported logging times of the loggers but no discrepancy was identified. It remains possible however, that an error may have been present in the equipment.

A similar effect is present in the concurrent temperature results (Figure 37). The peak high temperature of the outdoor treatment occurred two-hours ahead of all other treatments. Temperatures under rowcovers may have increased more rapidly than outdoors, causing the peak temperature shift. To a lesser degree, a similar shift was observed in high tunnel experiments (Chapter 3).

The highest temperatures were recorded under one layer of Typar covered with greenhouse plastic during daytime and nighttime from 29-31 Jan. 2010 (Figure 37, Table 19). Minimal differences were evident between one layer of Typar covered with perforated plastic and two layers covered with perforated plastic during daytime hours. Temperatures under the winter blanket and two layers of Typar were similar but exhibited lower daytime temperatures than the perforated plastic/Typar treatments. Temperature recorded under greenhouse plastic with one layer of Typar was appreciably warmer at night than all other treatments. The coolest temperatures under rowcover treatments were recorded under perforated plastic with one layer of Typar. The average outdoor temperature was -8.3°C and the highest average temperature under rowcover treatments was under greenhouse plastic with one layer of Typar (-2.0°C). When a minimum low temperature of -17.8°C was recorded on 30 Jan. at 8:00 am, temperature under greenhouse plastic with Typar was -11.3°C. However, when the maximum temperature of 24.9°C was recorded under the greenhouse plastic the outdoor temperature was only 4.9°C.

Cumulative heat units (CHU) were calculated starting 20 Nov. 2009, when all plastic materials were applied to the rows (Figure 38). Cumulative heat units with greenhouse plastic and with one layer of Typar was 803 compared to 581 and 566 CHUs, respectively, under the two perforated plastic treatments. Two layers of Typar and winter blanket recorded 447 and 440 CHUs over the entire period. The total outdoor CHUs were 337. Heat units accumulated between 14 Dec. and 25 Jan. was minimal for all treatments and little plant growth occurred during that period.

More plants survived (86.7 percent across all three varieties) under one layer of Typar covered with greenhouse plastic than under any other application (Figure 39). Survival under all other applications was three plants or fewer. The perforated plastic, double layer Typar, and winter blanket treatments were not noticeably different from one another.

The results of this pilot study suggest that rowcover applications provide extensive winter protection and allow plants to grow in an otherwise inhospitable environment. However, these results can only be useful as background from which to design further experiments and do not provide conclusive evidence due to the unreplicated design and lack of yield results. From the results of this experiment, further work could focus on using one layer of Typar under greenhouse plastic and one layer of Typar under perforated plastic. These applications provided the highest protection based on plant mortality and offer increased warmth on cooler days. There appear to be no advantages in using a second layer of Typar as reflected by light transmission, temperature, and cumulative heat units.

Areas of future study may include ventilation treatments, temperature control, and weed pressure. These rowcovers remained in place and fully unventilated throughout the experiment. Perforated plastic was chosen for its potential to provide some ventilation but no attempt was made to quantify its effect. A concern for using greenhouse plastic is the potential for very high unmitigated temperatures that might occur during the warmest periods. Understanding when weed growth occurs in the winter environment will also aid in low tunnel management. Weeds were observed germinating in late fall in the gap between plastic mulch and the rowcover and were abundant in the spring.

Tables

Table 17. Low tunnel size specifications and rowcover materials used.

Specification	Size (m)
Row cover width per row:	3.0
Row length:	25.0
Minimum product per row:	75.0
Row width under hoops:	1.2
Low tunnel footprint:	30.0
Total length conduit/row:	100.5
Total length rebar/row:	25.3

Table 18. Low tunnel products, costs, and treatments.

Low Tunnel Product Specifications					Rowcover Treatments							
Product	Source	Purchase Size (m^2)	Retail Cost	Cost/m^2	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8
Perforated Row Cover (500 holes per m^2; 50 µm; 10.0 m x 150.0 m)	Dubois Agrinovation, Saint-Remi, Quebec, Canada	1500	$ 230.00	$ 0.15			1x	1x				
Sun Master 152 µm Greenhouse Plastic (3.0 m x 76.2 m)	Farmtek, Dyersville, IA	229	$ 275.00	$ 1.20	1x	1x						
Typar; Dupont 5131 42.2 g per m^2 (3.0 m x 335.3 m)	Autoverters, Inc., Roanoke Rapids, NC	1006	$ 500.00	$ 0.50	2x	1x	2x	1x	2x		1x	1x
Winter Protection Fabric (3.7 m x 45.7 m)	Griffin Greenhouse and Nursery Supplies, Tewksbury, MA	169	$ 265.00	$ 1.57						1x		
Schedule 40 PVC Conduit (1.3 cm x 6.0 m)	Local Plumbing Supply Store	610	$ 360.00	$ 0.59	*Rows 1 thru 6 supported with conduit and rebar*						*Wire hoop supports*	
Rebar (1.3 cm x 6.0 m)	Local Masonry Supply Store	91	$ 80.00	$ 0.88								

Table 19. Temperature under different rowcover applications from 29-31 Jan. 2010.

	Outdoor	Winter Blanket[z]	Typar[y] (2x)	Perf. Plastic[x], Typar	Perf. Plastic, Typar (2x)	Greenhouse Plastic[w], Typar
Average	-8.3	-5.9	-6.5	-5.8	-5.4	-2.0
Std Dev	7.1	7.3	7.8	9.5	8.9	10.0
Min	-17.8	-15.3	-16.3	-16.4	-15.4	-11.3
Max	8.0	11.7	12.1	16.3	16.0	24.9
1/30/10 8:00	-17.8	-15.0	-16.3	-16.4	-15.3	-11.3
1/31/10 12:00	4.9	11.7	12.1	16.3	16.0	24.9

[z]Winter Protection Fabric, Griffin Greenhouse and Nursery Supplies, Tewksbury, MA.
[y]Typar®, 42.2 $g{\cdot}m^{-2}$ (1.25 $oz{\cdot}y^{-2}$) spundbonded rowcover; Autoverters, Inc., Roanoke Rapids, NC, supplier; hereafter referred to as "Typar"; also known as Dupont 5131.
[x]Dubois Agrinovation, Saint-Remi, Quebec, Canada; 50 µm, 500 holes/m^2.
[w]Sunmaster 152 µm Greenhouse Plastic, Farmtek Inc., Dyersville, IN.

Figures

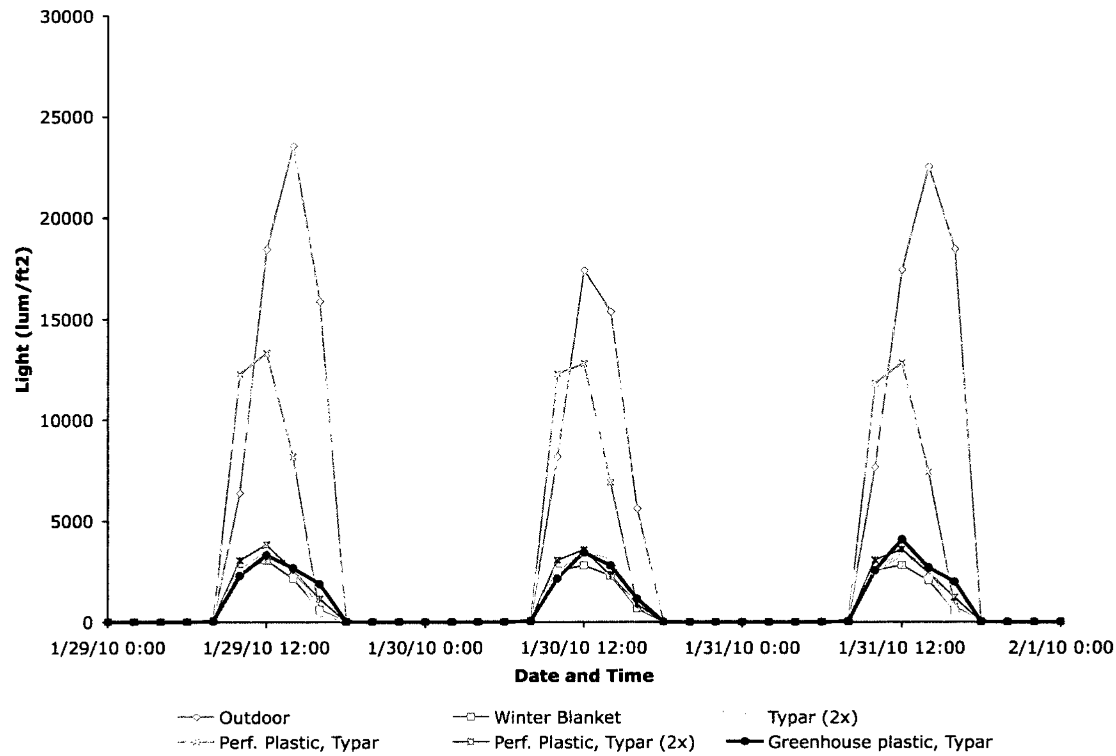

Figure 36. Light transmission under different rowcover applications from 29-31 Jan. 2010.

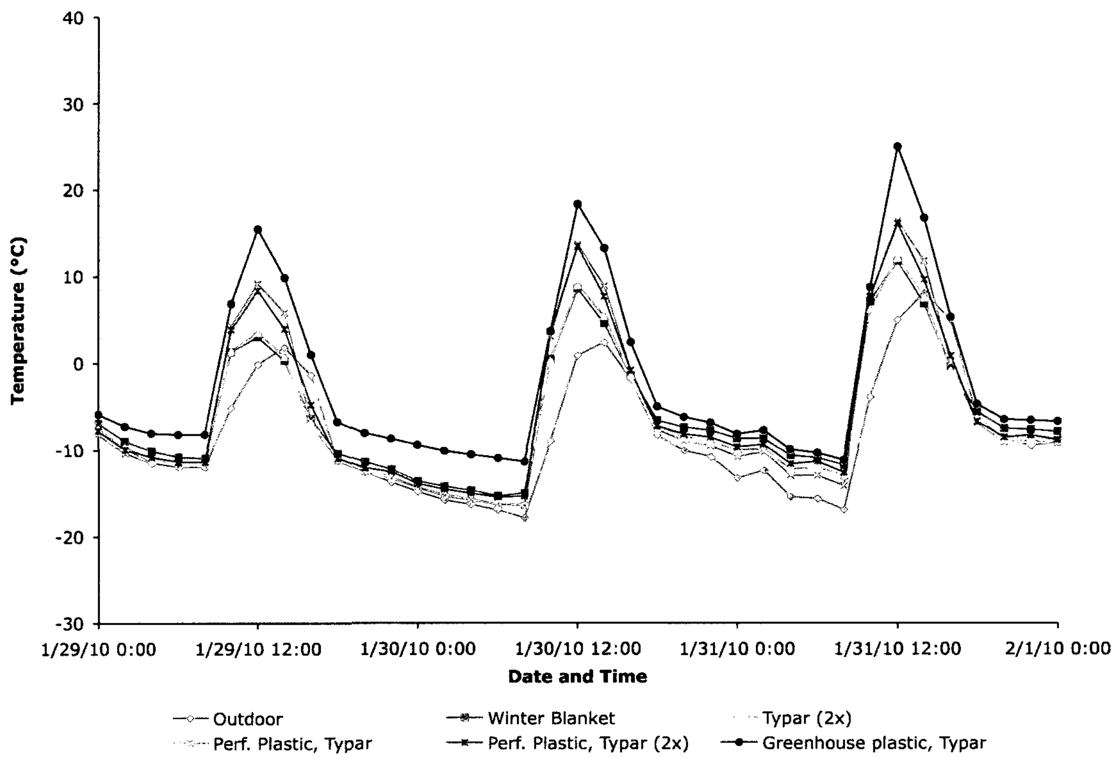

Figure 37. Temperature (°C) under rowcover applications from 29-31 Jan. 2010.

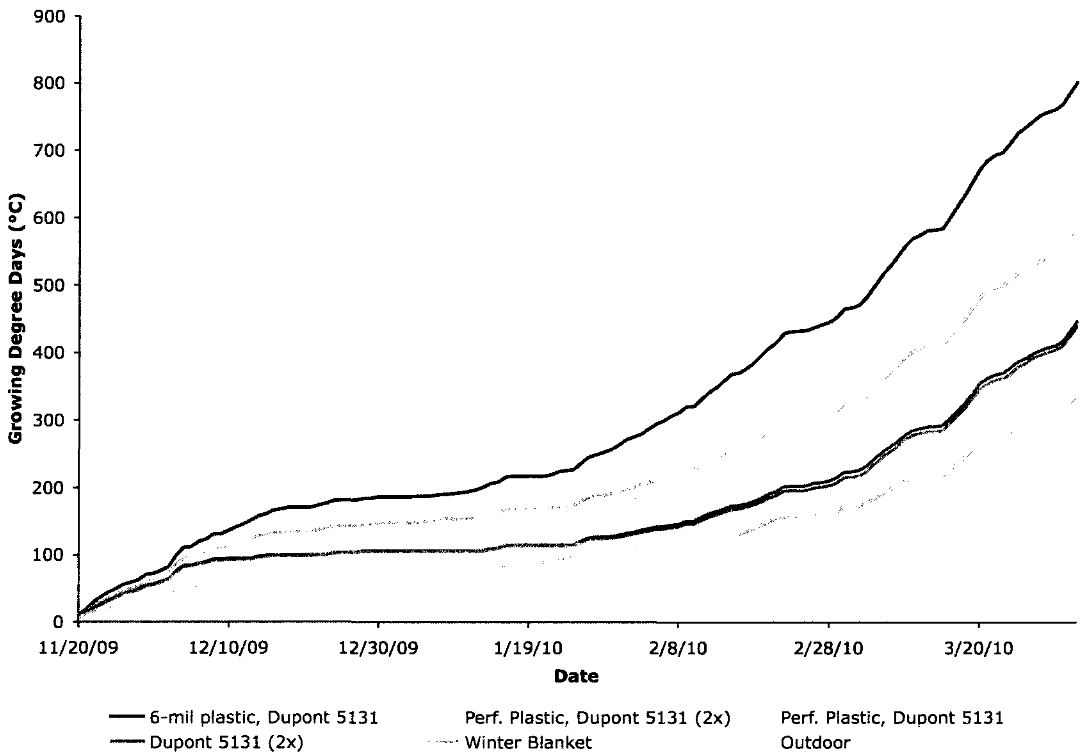

Figure 38. Cumulative heat units (°C, base 4.4) from 20 Nov. 2009 to 2 Apr. 2010 under rowcover applications.

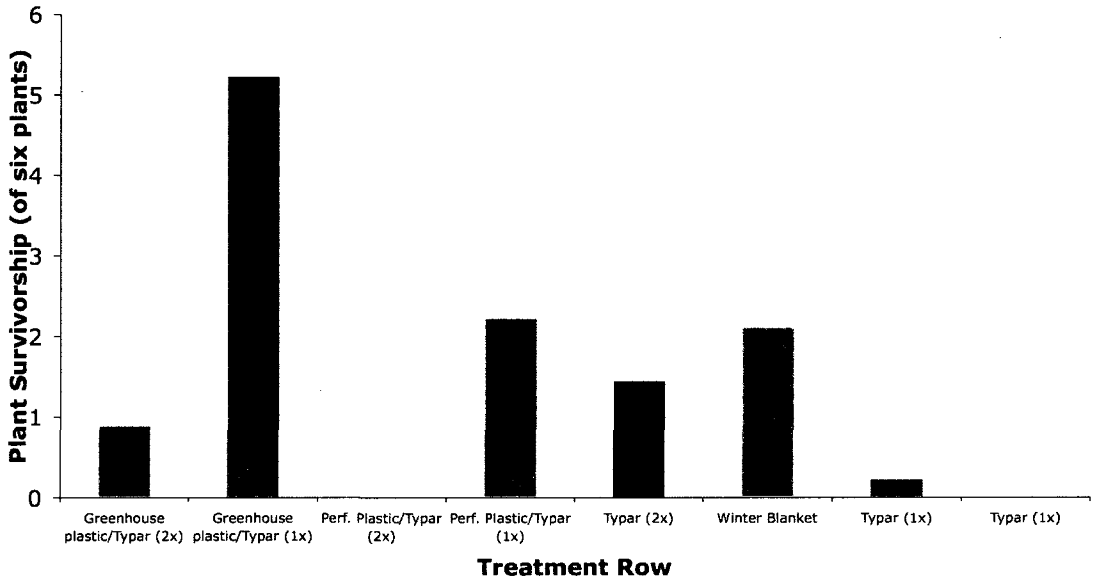

Figure 39. Average survival of six plants under different rowcover applications.

CHAPTER VI

ECONOMIC ANALYSIS OF WINTER SPROUTING BROCCOLI IN A 17 FT X 96 FT UNHEATED HIGH TUNNEL

Introduction

Vegetable farming in New England is characterized by a cooler climate and shorter growing season relative to other regions in the United States. As a result, many New England farmers use season extension methods including high tunnels to increase yield and income from their crops. High tunnels are most commonly used for summer tomato production, and tunnels are often fallow during winter months. Due to the high value of tomatoes as compared with alternative summer crops, crop rotation in tunnels is uncommon.

In studies at the University of New Hampshire, winter-sprouting broccoli (*Brassica oleracea* var. Italica) has shown potential as a crop that can be grown over winter in high tunnels without supplemental heat. This crop is little known in North America, but is widely grown by niche vegetable producers and home gardeners in Britain. It is biennial and relatively winter-hardy, producing a harvestable crop in March-May after August-September planting. The harvested product differs from typical broccoli grown in the U.S. in that it produces many long lateral shoots with purple, green or white florets, and is very mild flavored.

No supplemental heat is required to grow winter sprouting broccoli; many farmers already have necessary tunnel infrastructure in place. It has potential to attract business in early spring when demand for local vegetables is high and can be marketed as a niche crop to restaurants, cafés, coops and other markets. Winter sprouting broccoli is suitable for organic, conventional, and IPM growing practices.

Winter-sprouting broccoli will likely be most suited for diversified farms, particularly those farms that employ high tunnels for crop production. Several growers in New Hampshire were asked to participate in a study to identify and solve barriers for commercial production of this crop. Each cooperating grower's environment was slightly different. Variations existed in growing practices (organic, IPM, conventional) and in marketing strategies (CSA, farmer's markets, roadside stands, restaurant/café). Through interviews, cooperating growers provided detailed descriptions of the growing environments and yield data.

Materials and Methods

Six New Hampshire growers were supplied with winter sprouting broccoli transplants following an agreement to participate in a farmer-partnership grant sponsored by Northeast Sustainable Agriculture Research Education (NESARE). Organic transplants for growers were seeded 18 Aug. 2009, and grown in a certified greenhouse at UNH Woodman Farm, Durham, NH, prior to delivery to each farmer. Conventional transplants were seeded 19 Aug. 2009, and were also grown at UNH greenhouse facilities. Organic transplants were fertilized with fish emulsion at the specified manufacturers label rate.

Growers were visited once in the fall when transplants were delivered and once in the spring following harvest. Growers planted broccoli to accommodate their own production systems and to suit their marketing needs. Results from three of the original growers who were supplied with transplants and provided feedback during the post-harvest interview on 11 May 2010 are presented below.

Farmer A, Grafton County, NH

Winter sprouting broccoli was grown in a 30-foot by 96-foot unheated high tunnel with manual roll-up sides. The tunnel was not equipped with ventilation. Plant beds were located on the edge rows of the tunnel and spinach was planted in the interior beds. 150 transplants were planted in two 3-footwide beds using three rows per bed arranged in a diamond pattern with 12-inch spacing in each row. Plants were covered with two layers of a mid-weight spunbonded rowcover material late in the fall. No pest control practices were used, but rodents damaged three plants. Irrigation was provided on an as-need basis and was unnecessary during the winter.

Farmer B, Merrimack County, NH

Transplants were planted into 4-foot wide beds with two rows per bed with eight to ten inches between plants in a row. Most plants were transplanted two weeks after they were delivered and one small area was planted one week later. This small area remained stunted all winter. One layer of Agribon 19 rowcover was applied in late fall. Rowcovers were manually removed on warm days, but no active ventilation was provided to the high tunnel beyond opening end doors.

Farmer C, Merrimack County, NH

Transplants were planted in three single rows with 12-inch spacing between plants in a 24-foot by 48-foot unheated high tunnel with plywood endwalls. Soil stayed moist throughout with winter due to a high water table and no irrigation was necessary. Each of the three rows received a different secondary cover application: uncovered, Agribon rowcover, and hay mulch. Insect pressure was minimal, but Sluggo (Lawn and Garden Products, Inc., Fresno, CA) was used to control slugs.

Results

Farmer A

Plants were harvested during a two-week concentrated period from 15 Apr. to 1 May prior to being tilled under on 3 May. No storage was necessary and the harvested product was delivered wholesale to a local food coop where it was marketed as "No fossil Fuels Used". The grower harvested approximately 75 pounds which sold at $3 wholesale for a 0.6 pound bag. The product sold at retail price between $5-6 per bag and Farmer A was very positive about the crop and his success at marketing and selling. Timing was the major limitation to the crop and led to early harvest cessation in order to plant tomatoes in the high tunnel. In the future, Farmer A plans to produce winter broccoli in a tunnel destined for later tomato planting. Farmer A also believes he can increase his yields and sales during the next season beyond the first seasons' attempt.

Farmer B

A total 6.65 pounds of winter sprouting broccoli were harvested on 2 Apr., 12.5 pounds were harvested on 14 Apr., and 3 pounds were harvested on 24 Apr. for a grand total of 22.15 pounds. This was regarded as insufficient yield to meet the costs of production. Broccoli sprouts were sold as part of a CSA salad mix and a few were offered as choice items. Competition for available space was viewed as a limiting factor to growing this product during another season.

Farmer C

Plants were harvested from mid-March to April and yield was approximately 0.33 pounds per plant from surviving plants. Approximately one third of plants died in Agribon covered rows, half to two-thirds died in the uncovered row, and less than one third died in the hay-mulched row. Farmer C did not attempt to market the broccoli but distributed it freely to a positive response from friends and acquaintances.

Economic Analysis

Cultural procedures (Table 20) were developed following the results of three winter growing seasons at the University of New Hampshire and feedback from grant-cooperative growers in 2010. In addition, an economic analysis of high tunnel winter sprouting broccoli was completed to include investment costs (Table 21), annual returns and expenses (Table 22), and annual net returns (Table 23, Table 24). Each model incorporates the experiences at UNH Woodman Farm with those of cooperating growers.

Investment costs are calculated based on the purchase cost of a 17 ft x 96 ft Ledgewood Frame from Ledgewood Farm, Moultonborough, NH. Other costs in the model include endwalls, plastic cover, labor, secondary rowcover, and a secondary rowcover frame. The model for the secondary rowcover frame is adapted from Blomgren and Frisch (2007) and is constructed from 0.5-inch and 0.75-inch electrical conduit. The proposed model used in the investment calculations (Table 21) is constructed by placing supports at ten-foot intervals connected down the length of the tunnel with wire to keep rowcover elevated from the plant canopy. To construct a bow, two ten-foot lengths of 0.5-inch conduit are bent to form a 90-degree curve so that one end provides the vertical post and the opposite end is part of the horizontal support. A 10-foot 0.75-inch conduit connects the two horizontal 0.5-inch bows (Figure 40). Each completed bow is connected with wire at each edge and on the middle through the length of the tunnel. Plant spacing includes four 90-foot beds with two staggered rows at 12-inch spacing for a total of 576 plants per tunnel.

Variable costs included seeds and transplant supplies, fertilizer and soil amendments, bed mulch, irrigation, pesticides, packaging, and labor. Fixed costs include annual depreciation and annual interest on the primary structure, plastic cover, rowcover frame, and secondary rowcover. Also included were land costs, interest, and real estate tax. Annual net returns were calculated on receiving $5-$10 per pound and 0.35-0.69 pounds per plant consistent with harvest results from UNH and cooperating growers.

Discussion

The proposed budget did not include summer crop use of the high tunnel structure. In an ideal scenario, winter sprouting broccoli would occupy a high tunnel on its own or in combination with other crops during the scheduled portion of the year when tomatoes or other summer crops cannot be grown. A rotational growing scheme such as this would allow for distribution of the primary structure costs across sales of multiple crops. However, the winter sprouting broccoli would bear the full cost of the secondary rowcover structure.

Labor costs ($400) are 63 percent of the proposed variable costs and are divided equally between harvest and pre-harvest. Materials and supplies account for the remaining 37 percent. A potential investment cost that that was omitted from the proposed budget is a source of frost-free irrigation. This cost should be considered by growers attempting to produce winter sprouting broccoli in an unheated high tunnel that has previously been unused in the winter. The irrigation needs of winter sprouting broccoli have proven to be very minimal during the winter months over three years of experiments at the University of New Hampshire and by cooperating growers, however water needs are appreciable beginning in March.

There is no standard sale price established for winter sprouting broccoli and the prices that different markets will support are unknown. Farmer A successfully sold winter sprouting broccoli at a wholesale price of $5 per pound and projected he grossed $40-$50 per hour on his efforts. In that situation, the tunnel infrastructure was already established and multiple crops were grown simultaneously. Through the initial winter sprouting broccoli experiments, we projected farmers might be able to charge up to $10 per pound retail for the product. The current budget accounts for 32 hours of labor in variable costs. In order to gross $50 per hour in the current model, a grower would need to produce 400 pounds per tunnel and sell at a rate $8-$9 per pound or produce 350 pounds per tunnel and sell at $10-$11 per pound.

Winter sprouting broccoli provides diversification in crop rotation and high tunnel crops, diversification of fresh market sales, and offers a source of income during a season when sales are generally slow. It is most suited for commercial production in unheated high tunnels where some infrastructure is already in place since the ability of winter sprouting broccoli to generate enough profit to cover infrastructure costs is unproven. In our experience, there is a positive consumer response and the product can readily be sold. The challenges are in keeping production costs low in order to support labor and costs. We grew winter sprouting broccoli exclusively in experiments at UNH Woodman Farm. However, growers who are already practicing winter growing should first consider the product an addition, rather than a substitute, to other winter crops such as spinach, kale, or chard that are already recognized by consumers. Cultivar selection is important because later maturing cultivars might interfere with spring planting dates and we found that some cultivars possessed undesirable characteristics. The cultivars Santee, White Sprouting Early, and Red Spear were three of the top performing cultivars in our experiments in overall yield, earliness to maturity, and desirable characteristics such as attractiveness and tenderness. It is reasonable to expect winter sprouting broccoli plants to occupy high tunnel space from the beginning of October as transplants until at least mid-April when the harvest is completed.

Tables

Table 20. Cultural procedures for production of winter sprouting broccoli in an unheated high tunnel.

Step	Cultural Procedure (Action Required)	Week From Planting	Calendar Week
1	order seeds, transplant trays, transplant media, mulch, etc.	-8	26
2	soil testing	-8	26
3	seed into transplant trays in greenhouse	0	34
4	water as needed	0-4	34-38
5	make soil amendments to high tunnel	3	37
6	till high tunnel soil	3	37
7	form beds, lay mulch, place irrigation header	3	37
8	transplant into high tunnel	4	38
9	water as needed	4-12	38-46
10	pest monitoring; apply dipel as needed	4-12	38-46
11	install rowcover support and rowcover	12	46
12	venting, humidity control, water as needed	12-27	46-61(9)
13	check for harvestable shoots	28-29	62-63 (10-11)
14	side dress if needed	28-32	62-66 (10-14)
15	pest monitoring	30-38	64-72 (12-20)
16	harvest 2x per week	30-38	64-72 (12-20)

Table 21. Investment costs for winter sprouting broccoli production in a 17 ft by 96 ft unheated high tunnel.

Investment	Amount and Description		Rate per unit		Dollars	Totals
Structure Costs						
Frame[1]	1	per 17' x 96' frame	$3,625.00		$3,625.00	
Roll-up, 2 sides[1]	1	2 sides	$520.00		$520.00	
Lumber						
Base & side boards[2]	24	treated 2" x 10" x 16'	$1.37	per linear foot	$526.00	
Endwalls[2]	6	treated 4'x8' x 0.5"	$28.97	per board	$173.82	
Hardware and miscellaneous			$125.00		$125.00	
Construction Labor	32	hours	$12.50	per hour	$400.00	
						$5,369.82
Poly Cover[3]	1	6 mil 4 year, 36' x 100'	$4.23	per foot length	$423.00	
						$423.00
Secondary Rowcover[4]						
AG-19		30'x100'	$70.00	0		
AG-30		26'x800'	$735.00	0		
AG-50		30'x800'	$1,346.00	0		
TYPAR 5131	0.5	30'x200'	$345.00	1 100' length	$172.50	
						$172.50
Secondary Rowcover Frame						
2x4 support[2]	5		$4.62	per 8' board	$23.10	
3/4" 10' metal conduit[2]	10		$3.48	each	$34.80	
1/2" 10' metal conduit[2]	20		$1.89	each	$37.80	
wire/string/twine[4]		#9 Wire, 550'	$82.00	($0.15 per foot, 270 feet)	$40.50	
						$136.20
Land Investment[5]	0.06	acres	$10,000.00	per acre		**$600.00**
Total Investment Cost						**$6,529.02**

1. Ledgewood Farm Greenhouse Frames, Multounborough, NH
2. Home Depot, Lebanon, NH.
3. Farmtek, Dyersville, IA
4. Johnny's Selected Seeds, Winslow, ME
5. (Sciabarrasi, Hamilton et al., 2006)

Table 22. Annual returns and expenses for organic winter sprouting broccoli production in a 17 ft x 96 ft unheated high tunnel.

	Amount or Rate	Unit	Price or charge	Unit	Dollars	Totals
Receipts	300	pounds (576 plants)	$7.50	per pound	$2,250.00	**$2,250.00**
Marketing Costs[1]			20%	of price received		**$450.00**
Production Expenses						
Transplants						
Seeds[2]	6	100 seeds	$8.95	Each	$53.70	
Seed Tray[3]	13	806's	$0.46	each	$5.98	
Soil Medium (Vermont Compost)[4]	8	quarts	$0.47	per quart of a 60 quart bag	$3.76	
Production						
Lime, preplant[5]	82	pounds	$0.20	per pound	$16.40	
Fertilizer, preplant	50	pounds	$17.00	per 50# bag	$17.00	
Mulch[4]	400	feet	$495.00	per 4' by 4000' feet	$49.50	
Pesticides[4]	0.5	ounces	$24.95	per lb	$0.78	
Drip Tape[6]	400	feet	$37.95	per 1000 feet	$15.18	
Irrigation Header[6]						
Supply Tube	15	feet	$14.95	per 100 feet	$2.24	
Cap	1	each	$1.29	each	$1.29	
Couplers	4	each	$0.50	each	$2.00	
Labor						
Preplant prep	2.5	hours	12.5	hour	$31.25	
Transplant	3	hours	12.5	hour	$37.50	
Pest Control	0.5	hours	12.5	hour	$6.25	
Weed Control	5	hours	12.5	hour	$62.50	
Rowcover	5	hours	12.5	hour	$62.50	
Harvest (2days per week, 8 weeks)	16	hours	$12.50	hour	$200.00	
Packaging[5]	0.25	roll of 2000	$50.00		$12.50	
Miscellaneous Variable Costs[1]			$20.00	per tunnel	$20.00	
Operating interest[1]	$400	dollars	8%	interest	$32.00	

	Amount or Rate	Unit	Price or charge	Unit	Dollars	Totals
Total Variable Production Expenses						**$632.33**
Annual depreciation (zero salvage value)						
Structure	$5,369.82	investment	10	years	$536.98	
Plastic Cover	$423.00	investment	4	years	$105.75	
Rowcover Frame	$152.10	investment	10	years	$15.21	
Rowcover	$172.50	investment	3	years	$57.50	
Annual interest charge on investment						
Structure	$2,684.91	avg. investment	7%	interest	$187.94	
Plastic Cover	$211.50	avg. investment	7%	interest	$14.81	
Rowcover Frame	$76.05	avg. investment	7%	interest	$5.32	
Rowcover	$86.25	avg. investment	7%	interest	$6.04	
Land Costs						
Interest[1]	$600	investment	4%	interest	$24.00	
Real estate tax[1]			$15.00	tunnel	$15.00	
Other fixed costs[1]			$50.00	tunnel	$50.00	
Total fixed production expenses						**$1,018.55**
Annual net returns (receipts less marketing costs less production expenses)						**$149.12**

1. (Sciabarrasi, Hamilton et al., 2006)
2. High Mowing Seeds, Wolcott, VT
3. Griffin Greenhouse Supply, Tewksbury, MA
4. Johnny's Selected Seeds, Winslow, ME
5. Fedco Seeds, Waterville, ME
6. Farmtek, Dyersville, IA

Table 23. Annual net returns before costs.

Pounds Produced (576 plants)		Prices Received Per Pound					
Per Plant	Per Tunnel	5	6	7	8	9	10
0.35	200	$ 1,000.00	$ 1,200.00	$ 1,400.00	$ 1,600.00	$ 1,800.00	$ 2,000.00
0.43	250	$ 1,250.00	$ 1,500.00	$ 1,750.00	$ 2,000.00	$ 2,250.00	$ 2,500.00
0.52	300	$ 1,500.00	$ 1,800.00	$ 2,100.00	$ 2,400.00	$ 2,700.00	$ 3,000.00
0.61	350	$ 1,750.00	$ 2,100.00	$ 2,450.00	$ 2,800.00	$ 3,150.00	$ 3,500.00
0.69	400	$ 2,000.00	$ 2,400.00	$ 2,800.00	$ 3,200.00	$ 3,600.00	$ 4,000.00

Table 24. Annual net returns after marketing costs, variable costs, and fixed costs.

Pounds Produced (576 plants)		Prices Received Per Pound					
Per Plant	Per Tunnel	5	6	7	8	9	10
0.35	200	$ (1,100.88)	$ (900.88)	$ (700.88)	$ (500.88)	$ (300.88)	$ (100.88)
0.43	250	$ (850.88)	$ (600.88)	$ (350.88)	$ (100.88)	$ 149.12	$ 399.12
0.52	300	$ (600.88)	$ (300.88)	$ (0.88)	$ 299.12	$ 599.12	$ 899.12
0.61	350	$ (350.88)	$ (0.88)	$ 349.12	$ 699.12	$ 1,049.12	$ 1,399.12
0.69	400	$ (100.88)	$ 299.12	$ 699.12	$ 1,099.12	$ 1,499.12	$ 1,899.12

Figures

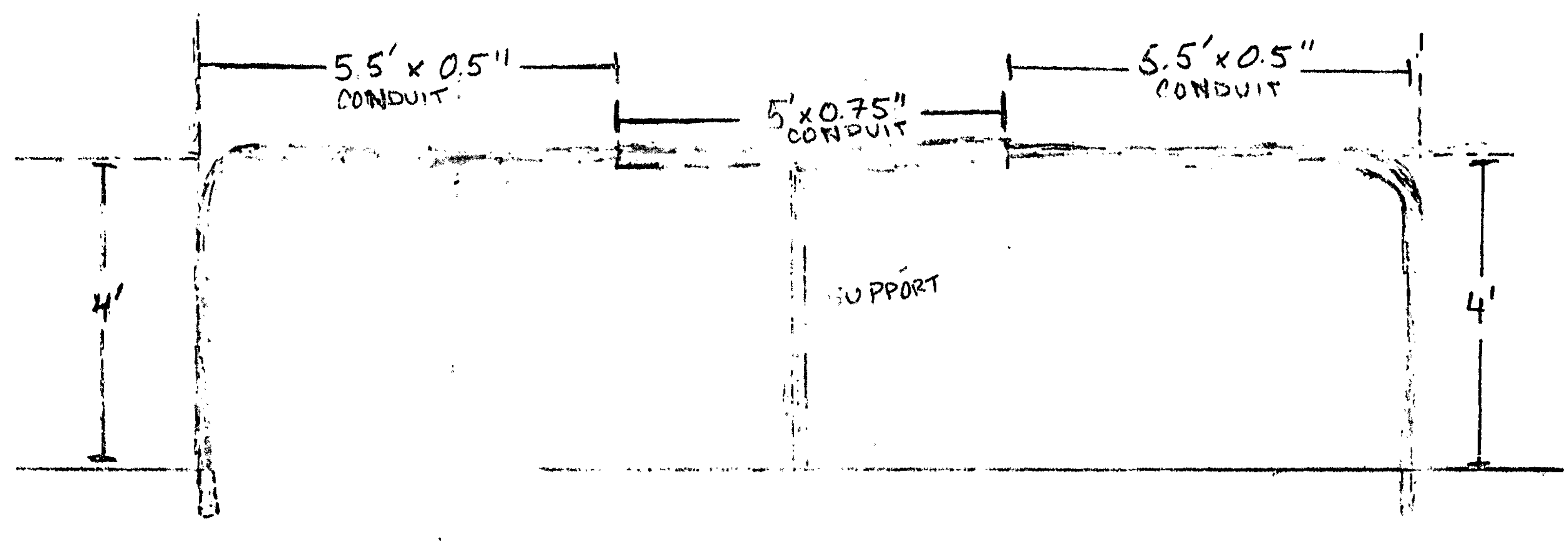

Figure 40. Sketch diagram of secondary rowcover construction profile.

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